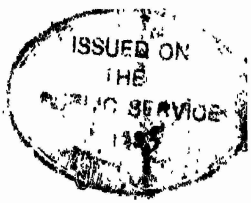
IRRIGATION WORKS

IN INDIA

AND

EGYPT



BY

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"Behold, I will do a new thing; now it shall spring forth; shall ye not know it? I will even make a way in the wilderness, and rivers in the desert."—ISAIAH xliii. 19.

London:

E. & F. N. SPON, 125 STRAND

New York:

SPON & CHAMBERLAIN, 12, CORTLANDT STREET.

1893

Irrigation Works in India & Egypt

/ Robert Burton Buckley /1893

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PREFACE.

In 1880, during my last period of furlough from India, Messrs. Allen & Co., of Waterloo Place, published for me 'The Irrigation Works of India and their Financial Results,' a book which gave a brief history and description of the Irrigation Works of India, with some information concerning the profits and losses accruing from them. I did not attempt, in that book, to treat of the principles which regulate the design of Irrigation Works, or of the practice which prevails in their construction. The task which I set myself, during my present furlough, was to enunciate those principles and to illustrate that practice within the compass of a single volume of moderate size: the difficulty has been to compress the matter within the space assigned to it. In some respects the older book, though obsolete in financial details, may be taken as a useful supplement to this one, as it contains fuller general descriptions of the works than could be given here.

During the winter of 1891 I spent three months' privilege leave in Egypt, where, under the kindly and hospitable guidance of Colonel Justin Ross, R.E., who was at that time Inspector General of Irrigation, and of my old Indian friends Mr. Foster and Major Hanbury Brown, R.E., who now divide between them the office which Colonel Ross then held, I travelled over many of the Irrigation Works of Lower and of Upper Egypt. The references to the Egyptian Irrigation Works which appear in this book are due to that visit and to assistance given me by the officers just mentioned.

In 'Irrigated India,' 1893, the Hon. Alfred Deakin, formerly Chief Secretary and Minister of Water Supply, Victoria, who lately

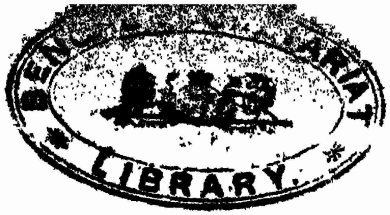
visited most of our great Irrigation Works, points out the need of a book on the Irrigation Works of India which might be "a manual of construction for many years to come, of the greatest value to the Colonies. If complete, it would at the same time offer to the outer world the best justification for British supremacy in India, and the best evidence, from facts and actions, of the large-minded generosity and courage of its rule." I hope that this book may, in some measure at least, supply a deficiency which has been felt by many who are interested in Irrigation.

I am indebted to the Secretary of State for India for the use of the plates from which the frontispiece and the rainfall map have been produced, and to the Local Governments of Bengal, the North-West Provinces, the Punjab, and Madras, respectively, for twelve of the maps, illustrating the local works, which appear in the book. Mr. Colvin, the Secretary of the Public Works Department at the India Office, arranged that I should have access to the records of his department, and I am in no small degree indebted to him and to other officers of the India Office. I have also to acknowledge the assistance which I have received from Sir Guilford Molesworth and from several officers in India, especially to Mr. Hughes of Bombay, Colonel Ottley, R.E., of the Punjab, and Colonel McNeile, R.E., and Mr. Odling of Bengal, for the use of plans of various works. Descriptions of works have, in some cases, been taken almost verbatim from the official reports which are quoted in foot-notes.

I have appended a list of books and publications which students of Irrigation will find interesting. Many of them are out of print: they can be seen either at the Library of the India Office or at the Institution of Civil Engineers.

R. B. B.

March 1893.



LIST OF BOOKS AND PUBLICATIONS ON IRRIGATION.

TITLE.	AUTHOR.	PUBLISHER OR PLACE OF PUBLICATION.	DATE.
Irrigated India	Hon. A. Deakin ..	Messrs. Thacker & Co., London.	1893
Irrigation Canals and other Irrigation Works.	P. J. Flynn	San Francisco, California	1892
Irrigation in India	H. M. Wilson ..	Govt. Printing Office, Washington.	1892
Le Irrigazione nell' Egitto con tre carte annesse.	.. ..	Roma	1892
The Nira Canal. A selection from Proceedings of the Government of Bombay.	.. ..	Bombay	1891 1890
Irrigation Manual	Lt.-Gen. J. Mullins, R.E.	Messrs. E. & F. N. Spon, London.	1890
Les Irrigations	A. Ronna	Firmin-Didot et Cie., Paris	1888–89–90
Egyptian Irrigation	W. Willcocks	Messrs. E. & F. N. Spon, London.	1889
Irrigation in California. The field, water-supply, and works.	W. Ham Hall ..	State Office, California ..	1888
Agricultural Engineering in India ..	J. R. C. Nicholls ..	Office of 'Engineering,' London.	1888
L'Irrigation en Egypte	J. Barois	Imprimerie Nationale, Paris.	1887
Irrigation Development: France, Italy, and Spain.	W. Ham Hall ..	State Office, Sacramento	1886
Hydraulic Works	L. D'A. Jackson ..	Messrs. W. Thacker & Co., London.	1885
Irrigation in Western America ..	Hon. A. Deakin ..	Govt. Press, Melbourne	1885
Godaveri, Kistna, Cauveri Delta, and Penner Anicut System. A selection from Proceedings of the Government of Madras.	.. ..	Govt. Press, Madras ..	1883
Irrigation Works in Southern France	Claude Vincent ..	Govt. Press, Madras ..	1882
Continental Irrigation	H. L. Roth	Messrs. Trübner & Co., London.	1882
Report of the Indian Famine Commission, Part I. (C. 2591); Part II. (C. 2735); Part III. (C. 3086).	.. ..	Parliamentary Paper, London.	1880 & 1885
Appendices of the above, Nos. I. to V. (C. 3086).	.. ..	Parliamentary Paper, London.	1881
Roorkee Hydraulic Experiments ..	Capt. A. Cunningham, R.E.	Thomason College Press, Roorkee.	1880–81
The Irrigation Works of India and their Financial Results.	R. B. Buckley ..	Messrs. W. H. Allen & Co., London.	1880
Irrigation in India in connection with Indian Deficits.	.. ..	Messrs. Wyman & Co., Calcutta.	1877
Les Irrigations dans le Département des Bouches-du-Rhône.	J. A. Barral	Imprimerie Nationale, Paris.	1877
Les Irrigations dans le Département Vaucluse.	J. A. Barral	Imprimerie Nationale, Paris.	1876
Irrigation Works in India, Lectures on the.	Col. F. H. Rundall, R.E.	School of Military Engineering, Chatham.	1876

TITLE.	AUTHOR.	PUBLISHER OR PLACE OF PUBLICATION.	DATE.
Sardah Canal Project, Report on the.	Capt. J. G. Forbes, R.E.	Oudh Government Press, Lucknow.	1871
Irrigation in Southern Europe ..	Lieut. C. C. S. Moncrieff, R.E.	Messrs. E. & F. N. Spon, London.	1868
Reservoirs in the Deccan Rivers ..	G. R. Carroll	Education Society's Press, Bombay.	1867
Godaveri District, Results of Irrigation Works in the.	Gen. Sir A. Cotton, R.E.	Messrs. Trubner & Co., London.	1867
Ganges Canal. Controversy between Sir Proby Cautley and Sir Arthur Cotton.	.. ..	Printed for Private Circulation, London.	1863–65
Report on the Ganges Canal	Capt. J. Crofton ..	P. W. Dept., Calcutta ..	1865
A Project for Canals of Irrigation and Navigation from the Sone River in South Behar.	Lt.-Col. C. H. Dickens, R.E.	Public Works Dept. Press, Calcutta.	1861
Ganges Canal Works, Report on the	Col. Sir Proby Cautley, K.C.B., F.R.S.	Messrs. Smith, Elder & Co., London.	1860
The Cauveri, Kistnah, and Godaveri. A Report on the Irrigation Works on those rivers.	Capt. R. Baird Smith, R.E., F.G.S.	Messrs. Smith, Elder & Co., London.	1856
Professional Papers of Madras Engineers.	.. ..	Madras	1856
Canal Irrigation of Rohilcund, Report on the.	Capt. W. Jones, R.E.	Thomason College Press, Roorkee.	1855
Italian Irrigation	Capt. R. Baird Smith, R.E., F.G.S.	Messrs. Blackwood & Sons, Edinburgh.	1852–53
Western Jumna Canals, Memo. on the.	Major W. E. Baker, R.E.	Messrs. Smith, Elder & Co., London.	1849
Central Doab Canal, Report on the	Major T. Proby Cautley, R.A.	.. ..	1840

Roorkee Professional Papers.

These volumes contain many papers describing Indian Irrigation Works, and treating of their design, the duty and distribution of water, &c. *See* FIRST SERIES, Vol. I., pages 37, 57, 224, 278, 366; Vol. II., pages 18, 112, 145, 195, 203, 214, 308; Vol. III., pages 74, 319; Vol. IV., pages 233, 330, 337, 399, 411; Vol. V., pages 1, 161, 272, 375, 396; Vol. VI., pages 37, 267, 361; Vol. VII., pages 75, 189, 207, 301, 329. And SECOND SERIES, Vol. I., pages 40, 85, 360; Vol. II., pages 31, 38, 69, 141, 145, 378, 384; Vol. III., pages 39, 302, 351, 372, 394; Vol. IV., pages 8, 27, 122, 144, 211, 236, 405; Vol. V., pages 205, 408; Vol. VI., pages 55, 89, 278, 286, 374; Vol. VII., pages 19, 57, 85, 227, 287, 307, 357; Vol. VIII., page 25; Vol. IX., pages 49, 63, 125.

Proceedings of the Institution of Civil Engineers.

These Proceedings contain several papers connected with Irrigation, the principal ones are in the following volumes:—Vol. XXV., Greathed; Vol. XXVII., Login; Vol. XXVII., Wilson; Vol. XXXIII., Gordon; Vol. XXXIV., Latham; Vol. LI., Wilson; Vol. LVII., Byrne; Vol. LVIII., Buckley; Vol. LXV., Target; Vol. LXXI., Fahey; Vol. LXXIII., O'Mearo; Vol. LXXIV., Ritso; Vol. LXXXVIII., Willcocks; Vol. CV., Fox.

Selections from the Proceedings of the Government of India, in the Public Works Department.

The following "Selections," which refer to Irrigation Works, can be obtained from the Superintendent of Government Printing, Calcutta. They contain plates:—No. CCXV., Periyar Irrigation Project, Madras; No. CCIV., Orissa Coast Canal, Bengal; No. CCXVII., Buckingham Canal, Madras; No. CCXVIII., Rushikulya Project, Madras; No. CCXIX., Palar Anicut System, Madras; No. CCXXXI., Zhara Karez Irrigation Scheme, Baluchistan; No. CCXXXII., Betwá Canal Project, North-West Provinces; No. CCXL., Failure of the Kali Nadi Aqueduct, Lower Ganges Canal; No. CCXLVIII., Sidhnai Canal Project, Punjab.

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NOTE.—Appendices I. to IV. are reprinted, with the kind permission of Mr. C. W. Odling, from a Memorandum by him which is used as a Manual in Bengal. Appendices VI. and VII. are reprinted from the Punjab Irrigation Manual. Appendix VIII. is taken from the rules in force in the Punjab. Appendix IX, is taken. with the kind permission of the author, from his Note on High Masonry Dams. Appendix X. is mainly from a Report by Mr. Benton of the Punjab Irrigation Department. Appendix XII. is from the Report on the Nira Canal Project published by the Government of Bombay.

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IRRIGATION WORKS IN INDIA AND EGYPT.

CHAPTER I.

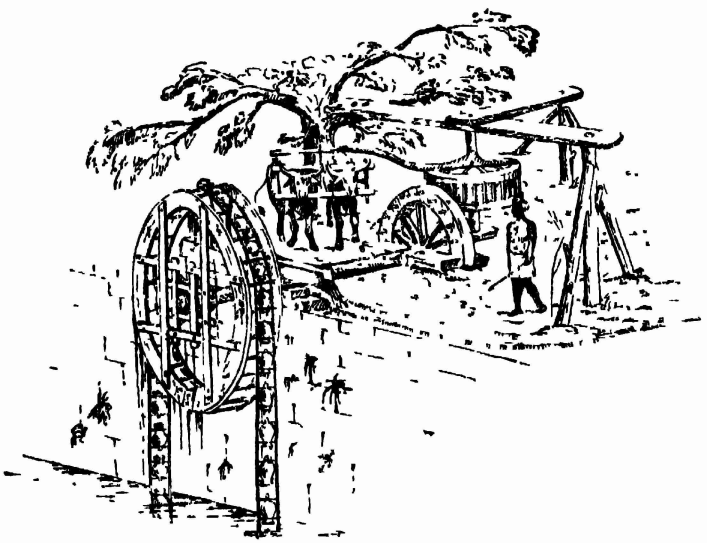
GENERAL AND DESCRIPTIVE.

Necessity for Irrigation in the Tropics — Inequalities of Rainfall — Mechanical Methods of Irrigation—Tanks and Reservoirs in different Provinces—Karezes in Baluchistan—Inundation Canals in India and in Egypt—Perennial Canals.

CULTIVATION in the tropics can rarely be conducted over any large extent of country without artificial watering of some portion, at any rate, of the crops. The rainfall, in some parts, may be utterly insufficient in every season to mature the crops: this is the case, for instance, in Sind and in parts of the Punjab, in India, where the rainfall of the year averages from 2 to 4 inches only, and in the whole basin of the Nile in Africa, where the rainfall, on large tracts, is practically nothing at all. Or the rainfall may be amply sufficient in total quantity, but badly distributed with reference to the seasons or to the requirements of the crops: this is the case in Southern India and in the Madras Province particularly, where the rain, though the total amount ranges from 40 to 60 inches in the year, generally falls in short periods, and it is not uncommon to have bursts of 12 inches in twenty-four hours. And even in parts of the Himalayas, where the rainfall varies from 50 to as many as 100 inches, crops grown on the terraces in the mountains are matured in the dry season by artificial irrigation. Hence, from the earliest ages, man has devised many systems for carrying the water to the land he cultivated. In those tracts where the total rainfall is inadequate, irrigation was effected either from wells or by leading water from perennial streams where they existed; and, in other districts, where the rainfall

was copious but unsuitably distributed, by the storage of the surplus water of one period in surface tanks and reservoirs, until, at another period, it was distributed on the fields. Plate III., page 10, shows the general distribution of the rainfall in India, and the frontispiece is a map of India, showing the irrigation-works, the rivers, their basins, catchment areas, and length of the main streams.

The old mechanical means employed for lifting water from wells, from streams, and from low-lying depressions, are of various kinds; all of them, with slight modifications, are to be found both in Africa and in Asia. The Persian wheel, which is found in various forms in Egypt and in Sind and the Punjab, consists of a series of earthenware pots

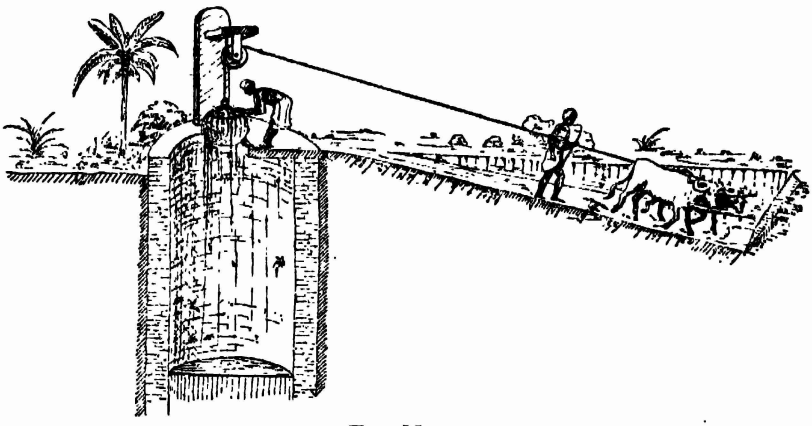


THE PERSIAN WHEEL.

revolving on a wheel with a horizontal axis; each pot delivers its contents into a trough, and then descends to the water to be filled again. In some cases the earthen jars are attached to endless ropes which revolve on the wheel, and sometimes they are attached to the circumference of the revolving wheel itself. These wheels are generally actuated by bullocks, and sometimes by camels or horses; and, in Egypt, one sometimes sees a camel and a donkey both harnessed together in the track. In some places, more particularly in the Fayoum in Egypt, where there are many small canals with comparatively rapid slopes and high velocities, these wheels—or *sakias*, as they are called—are driven, usually as undershot wheels, by the stream itself. In the Punjab

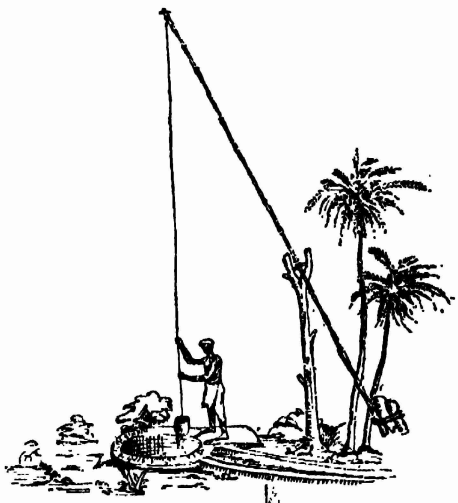
it is not an uncommon thing to see oxen lifting water by Persian wheels from depths of 50 and 60 feet for the irrigation of spring or summer crops.

Another system which is extensively used in India for the larger lifts is the *mote*. Two bullocks raise a leathern bag by means of a rope by



THE MOTE.

working over a pulley; sometimes a cord is attached to the lower end of the leathern bag, and by an ingenious but rough contrivance, the driver, by manipulating the lower cord, lets the water escape, from the lower end of the bag, when the bullocks have reached the end of their run and when the bag is at the top of the lift. But usually the mote is worked by two men, the driver, and another at the well head, who pulls the leathern bucket over the trough or channel in which the water runs.

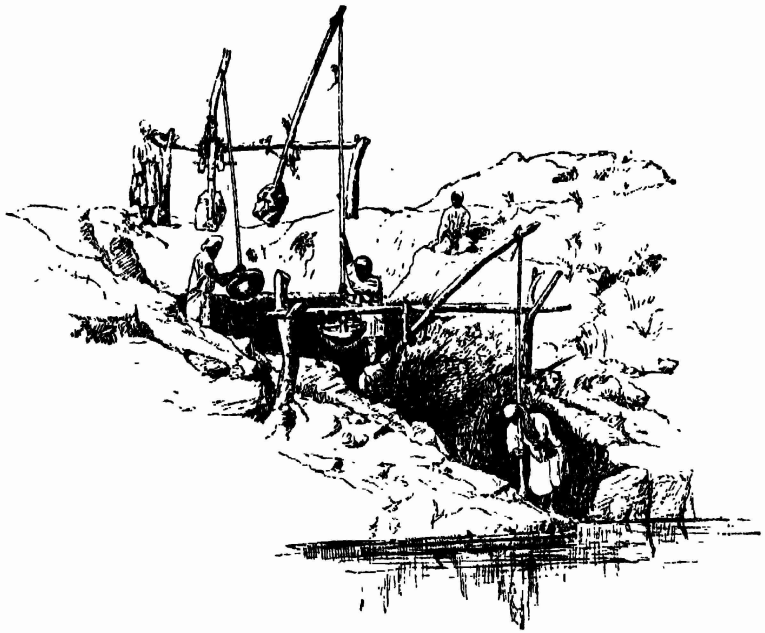


THE LÂT OR PICOTTAH.

For smaller lifts of 4 to 10 feet the appliance shown in the adjoining sketch is often used. This arrangement is called a *lât* in Upper India, a *picottah* in the south, and, in Egypt, under the name of the *shadouf*, it is extensively employed on the banks of the Nile.

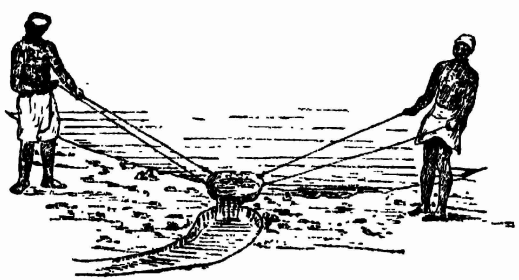
It consists essentially of a bucket, which is of leather, earthenware, or iron, as the case may be, hung to a pole which can oscillate in

a vertical plane; the short end of the pole is counterbalanced by a weight, usually a clod of earth or an old grindstone, so that the bucket, when full, requires but little force to raise it. The man working this



THE SHADOUF.

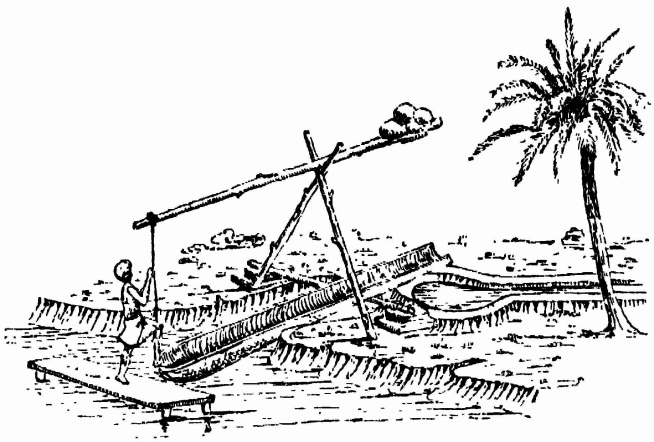
contrivance stands at the edge of the well and uses his weight to depress the bucket into the water, when, with but little force, it rises to the point where the water is delivered. Archimedean screws are largely



THE BASKET.

used in Lower Egypt for lifts not exceeding about 3 feet, and are said to give a much larger duty, for small lifts, than any of the other arrangements.

The basket scoop is used for smaller lifts of from 1 to 4 feet, and the *doon* is common in Bengal for lifts of about 2 or 3 feet. The doon is an oscillating trough, usually half the stem of a tâl tree hollowed out, which oscillates on a fixed centre, so that one end is alternately depressed into the water and raised above the level of delivery; the weight of the water is equalised by a counterbalance,



THE DOON.

so that the man, who stands over the water on a plank, can depress the end of the doon into the stream with his feet, and then, by stepping on to the plank and lifting slightly with his hands, can slope the trough towards the point of delivery, and thus enable the water to run out into the channel. Experiments made by Mr. Allan Wilson in Central India on these methods of raising water gave the following results:—

	Number of cubic feet of water raised one foot high in ten hours.
Bullock mote with two bullocks, one man	79,200
Picottah or lât with two men	57,600
„ „ one man	33,000
Basket scoop with two men	20,178

The results are reduced to the standard of 10 hours and a foot high for convenience of comparison. Inquiries made in Shahabad, in Bengal,* as to the average cost of irrigation by these different methods,

* Report on the Sone Canals, by Mr. H. C. Levinge, late Chief Engineer of Bengal.

gave the following results, the depth of the water in wells being about 15 feet:—

				Rs.	a.	p.
Cost of irrigating one acre with the	mote,	per crop	..	9	0	0
" "	lât	"	..	13	0	0
" "	basket	"	..	6	8	6
" "	doon	"	..	3	14	0

The irrigation with the basket and doon would have been from lifts of from 1 to 4 feet only. The figures given took account of the value and life of the material used, and of the cost of a man's labour. All these methods of raising water are more expensive than artificial irrigation, which, in India, costs on the average Rs. 3 an acre; but, in some cases, irrigation from wells really costs the actual cultivator little or nothing, as he only employs himself and his bullocks at times when there is no other work on hand.

It was reported by Colonel Baird Smith that, in 1860, there were 70,000 masonry wells and 280,000 temporary earthen ones, in the tract lying between the Jumna and the Ganges, from which 1,470,000 acres of crops were irrigated by lift, and, although this tract is now commanded by the Ganges Canal, many of these wells are still used to irrigate lands which are not watered by the canals.

One of the earliest systems of irrigation in India, in those districts where the rainfall is generally copious but unsuitably distributed during the season, was by surface tanks. They are found to some extent in all parts of India, and are common in the Shahabad district of Bengal, but are to be counted by thousands in Madras, where millions of acres of rice crops are irrigated from them. These tanks vary in size from a few acres to nine or ten square miles of water surface. They are usually formed by earthen embankments thrown across small local drainages, often of only two or three square miles in area, or by a series of such embankments thrown across the valleys leading from larger catchments: thus, in Shahabad, the Kao Nullah, having a catchment of 54 square miles and a maximum discharge estimated at 9000 cubic feet a second in flood, was crossed by a series of earthen embankments, which, completely blocking the course of the stream, formed a series of tanks, or *ahrahs* as they are locally called, of which the largest had a bank about 20 feet high and a water surface of four or five square miles. The floods were impounded in this series of tanks and utilised subsequently for irrigation; the surplus from one tank flowing by earthen escape channels to the one below. In years of very

heavy rainfall these local tanks were occasionally breached, and the supply stored was lost, and in years of deficient rainfall many failed to fill at all. In Mysore, on the Vedavutty river and its confluents, there is a somewhat similar chain system of tanks, except that they are mostly in torrents or rivers with much greater slope than the drainages of Bengal. In Bengal but few of these old tanks were provided with any masonry works for draining off the water or for regulating the discharge, but in Madras, where there are some 60,000 tanks,* the majority are provided with masonry works. The Madras tanks also depend mainly on local rainfall, but they are sometimes fed from rivers or streams by means of channels taking off above weirs constructed in the beds of the rivers. In a return given by the Madras † Government it appears that there are 1129 weirs across rivers or streams in Madras, each connected with a series of tanks, or with a single one. These weirs are exclusive of those connected with the larger irrigation works. The dependence on local rainfall renders the irrigation from these tanks to a certain extent precarious, but the area ordinarily irrigated from works of this kind in Madras exceeds 3½ million acres. In some cases the embankments, which with one or two exceptions are all made of earth, are built in gorges; thus the embankment of the Cummum tank in the district of Guntoor, which is over 100 feet high, is little more than 100 yards long, but the water surface of the reservoir is about eight square miles: while another example, the Chembrambaukam tank, about 14 miles from Madras, has an embankment 3 miles long which sustains a maximum depth of only 20 feet or so; it has a water-spread of 8·95 square miles and a capacity of 103 millions of cubic yards. In Mysore the Nuggar tank has an earthen embankment 84 feet high and 1000 feet long, and a tank is formed on a tributary of the river Lokain by a bank only 225 feet long but 117 feet high. In Bengal these surface tanks, in almost all cases, depend on their local catchment, but in Madras tanks are sometimes grouped together and fed from rivers. Plate I. shows one of these systems in the Salem district which has been greatly improved by Government since 1883 by the construction of a weir across the river Ponniar, and of a system of supply channels and sluices.

In Rajputana, in the districts of Ajmere and Mairwara, about 350 small tanks are maintained by Government; most of these are formed by earthen embankments, but one, near Ajmere, has a masonry dam 60 feet in height.

* Lecture I. by Col. F. H. Rundall, C.S.I., R.E., Chatham, 1876.

† Madras Irrigation Administration Report, 1878–9.

In the Bombay Presidency there are few rivers with a perennial supply, and the general scantiness of the rainfall has necessitated the construction of tanks in connection with nearly all works of irrigation. There are about thirty tanks maintained by Government, varying in size from a few acres up to 10 square miles of water-spread ;* most of these have earthen embankments varying in height from 30 to as much as 114 feet, but there are five or six with masonry dams of which the most noticeable are the Mutha Dam (Lake Fife), which has a maximum height of 98 feet, and the Bhatgarh Dam (Nira Canal), with a maximum height of 101 feet. The most lofty masonry dam in Bombay is that of the Chankapur tank in Khandesh, which is 121 feet high.

In Baluchistan, where the rainfall is scanty and very capricious, irrigation has been effected, from time immemorial, by a system not dissimilar to that of the *fontanili* in Italy. The country around Quetta, and the town itself, is alive with small streams of water which are derived from tunnels driven into the hill-sides, which tap underground springs. Each of these tunnels is called a *karez* and is generally only just large enough to permit a man to creep through it. The natives construct these *karezes* by sinking shafts from the surface about 50 to 80 feet apart, on the line which they intend the *karez* to follow, and then connecting the bottom of the shafts by a tunnel: the spoil is lifted up the shafts by baskets. In most cases there is no timbering or lining of any kind to the tunnel, and the result is that the *karezes* frequently fall in, and become choked. Plate II. shows a section of one of these old works which has recently been improved: the tunnel is driven about 5000 feet into the hill-side with a slope of 3 feet in 1000; the water is led from the mouth of the tunnel in an open channel to the fields, or to a tank where any surplus water may be stored until it is required. This karez is of the usual size—that is about 3 feet high by 20 inches broad—and it gives a discharge of about 9 cubic feet a second. The natives of the district are very clever in discovering likely places for these little irrigation works.

The practice of leading water from rivers and streams to irrigate adjacent lands was probably practised even before the time when the construction of tanks was undertaken. The most primitive system was that of making comparatively shallow cuts through the river bank into which the water flowed when the level of the river was raised by the regular floods which occur annually in most tropical streams. The canals

* A full list of these tanks, with statistics, is given in the 'Irrigation Manual' by Col. J. Mullins, R.E. (E. & F. N. Spon).

made on this system are called in India *Inundation* canals, and, in Egypt, where the system has found the fullest development, they are known by the name of *Nili*. The chief inundation canals of India are found in the basin of the Indus and of its five tributaries. It will be seen from the rainfall map (Plate III.) that these six * rivers, when they issue from the Himalayas, come upon a narrow belt at the foot of the mountains where the supply of rain varies from 40 inches downwards. About 100 miles from the hills they enter the arid region of Western India in which the rainfall varies from 10 inches to even as little as 2 inches in the year. In the course of ages the rivers have cut into the soil and left high land on either side of the valley, some 4 to 10 miles wide, in which each river follows a channel. The river has, in the course of many centuries, varied its position throughout the valley, leaving steep scarps on either side at the boundaries of its wanderings. The higher land on each bank, which is from 10 to 50 feet above the general level of these valleys, is called the *bhangar*, the lower land the *khadir*. The bhangar lands form the *doabs*, as they are called, lying between the six rivers; they are fertile in themselves, but cultivation depends entirely on the scanty rain, or, if artificial irrigation is not provided, on laborious irrigation by mechanical means from wells which are often 60 and 70 feet in depth. The khadir lands are naturally fertile, but the bhangar lands, though formed of good soil, are to a considerable extent covered with grass or brushwood, or entirely waste. As the rivers converge into the single stream of the Indus, near Mithankot, the bhangar lands gradually disappear and the low khadir extends right across between the rivers. Some of the inundation canals of the Punjab lie in the khadir of the higher reaches of the Sutlej and the Jhelum, but the majority of them, as shown in Plate IV., are in the area bordering on the confluence of the rivers with the Indus. The district of Multan, lying between the Sutlej and the Chenab, where rain hardly ever falls, is rendered beautifully fertile by a series of inundation canals, taken from both rivers, which are said to have been originally constructed by Afghan rulers left by Aurunzib. In the Derajat, on the right bank of the Indus, above Mithankot, there is a group of twelve inundation canals which have been constructed since the British rule, and in Muzuffarghar a corresponding group irrigates a tract some 12 miles broad on the left bank. The Upper Sutlej inundation canals are in the central portion of the *doab* lying between the Sutlej and the Ravi rivers. Here the face of the country is covered with traces of

* The description of the inundation canals is largely taken from 'East India Progress and Condition),' 1872–3. Printed 2nd June, 1874, for the House of Commons.

former life and prosperity. The cause of decay was due to the loss of water-supply consequent on the diversion of the river Bias, which formerly had an independent course to the Chenab, fertilising the land on either bank; but in 1790 it was diverted into the Sutlej, and its old bed became a dry ravine with a complicated system of deserted water-courses. A new system of inundation canals has now been carried into this tract from the Sutlej. The inundation canals of the Punjab aggregate some 3000 miles in length, and irrigate more than one million acres.

Lower down the course of the Indus, in the almost rainless tracts of Sind, and in the Native State of Bhawalpore,* the flood waters of the river are diverted by inundation canals on to the thirsty ground. The canals of Sind aggregate some 2600 miles in length, and irrigate on the average about 1,700,000 acres of crops,† which could not be grown at all without them. Sind is an alluvial plain, almost every portion of which has been swept by the Indus at some time or another. Traces of ancient channels are to be met with in every direction. The river has gradually worked its way from east to west. In 710 A.D. the invading Muslims found a Hindu dynasty at Alor, and the ruin of Alor was caused by the river moving to the west; the seat of government was then moved to the city of Brahmanabad, the ruins of which are now 45 miles from the river. The river, more or less continually, carries away its banks in one direction and forms new land in another: from Sukker to the sea, a distance of 300 miles, the banks are permanent at only three places, Sukker, Jhirk, and Kotri. At Sukker the river rushes through a narrow gorge in the limestone rocks, forming a rapid when the river is in flood. At Jhirk the river is not contracted, but there is rock on either side. At Kotri the hills approach on both sides, and the clay soil is deep and tenacious. Some of the largest canals in Sind were at first natural channels, others have been dug by various rulers of the country. They resemble natural water-courses in many respects, but they have been greatly improved since the British occupation. The largest of the Sind inundation canals is the Fuleli; originally it was a natural branch of the Indus which it rejoined about 16 miles below Haidarabad, but the outlet into the river was closed by a dam in the time of the Amirs, and the water was sent forward to feed other canals to the south. The improvement of the Fuleli by the British was commenced in 1856, when two new supply channels were cut from the Indus with

* See Frontispiece.

† In the year 1889–90 the area reached 2,300,000 acres.

very satisfactory results on the supply. This canal now irrigates about 300,000 acres of crops every year.

Inundation canals give, at best, a precarious system of irrigation; if the floods of the rivers, from which the canals are drawn, are regular, and the duration of the flood is sufficient, the cultivation is secure, provided that the canals have been cleared of the silt deposits of the previous year; but when the floods are low, or only remain for a short time at their full height, it is impossible to pass the necessary volume of water on to the fields, or even to give any water at all to many of them.

The Indus* begins to rise in April and May in consequence of the melting of the Himalayan snows, and continues to rise until about the middle of August, when it falls pretty rapidly until the beginning of October, after which the fall is more gradual. The water begins to flow into the Indus inundation canals in sufficient volume to allow the ground to be softened for ploughing when the river has risen to 12 feet on the gauge at Bukkur or 15 feet on the gauge at Kotri; these heights are usually attained in the month of June, and according as they are reached or not by the end of that month a fair forecast can be made of the probabilities of the inundation. When the cultivators see the month pass by without these heights being reached they become discouraged and curtail their preparations for cultivation in anticipation of a deficient supply of water. The 18th of June may be taken as a fair average of the latest date on which the river should rise to give a good prospect of successful cultivation, and if a further rise of two feet does not take place before the middle of July, the area of land which can be ploughed becomes restricted; for all land must be softened with water before it can be ploughed, and if the river has not risen sufficiently to irrigate the lands by flow, the cattle, which should be ploughing, have to be employed in lifting water by water-wheels to moisten the land. A considerable number of these wheels are employed in connection with these inundation canals, partly because the level of the water in the canals is entirely dependent on that of the river, consequently land which may be commanded at one stage of the river cannot be irrigated by flow at another, and partly because the original alignment of many of the canals of the Indus is in the low ground and does not give a command of the country.

The area of cultivation dependent on inundation canals maintained by Government in the Punjab and Sind, in the valley of the Indus and its tributaries, may be said to be about 3,000,000 acres; but in addition

* Revenue Report of Sind, 1887–88.

to the Government canals there are minor ones belonging to private owners in the Punjab, and there is an extensive system in the Native State of Bhawalpur, which extends for 300 miles along the left banks of the Sutlej, Chenab, and Indus. So that the gross area dependent on this system of irrigation is considerably in excess of 3,000,000 acres.

The inundation system has met with the fullest development in the valley of the Nile. The total area cultivated in Egypt is about 5,000,000 acres: the whole is irrigated, in one way or another, from the Nile and is more or less dependent on the height of the annual flood in the river. The canals in Lower Egypt, below Cairo, are, however, not as entirely dependent on the rise of the river as those in Upper Egypt, because there is a system of perennial canals, taking off above the barrage or weir across the Nile near Cairo, which are more under control than the inundation canals of Upper Egypt. The whole area of Egypt, however, is dependent to a large extent on the maximum rise and duration of the floods, for the perennial canals of Lower Egypt act in the same way as inundation canals during the flood season, that is to say, that although they never run quite dry, the depth of water in them and the consequent volume discharged into the canals is enormously increased during the annual flood. The importance of the height attained by the Nile may be gauged by the fact that in 1877, when the Nile flood was the worst of any of which accurate statistics exist, nearly one million acres,* or one-fifth of the culturable land of the whole of Egypt, was left waste, and the loss of revenue alone was over one million sterling; and again in 1888, when another low flood, but not an abnormally low one, occurred, the area uncultivated in Upper Egypt alone was 300,000 acres, or about one-seventh of the area above Cairo which is watered by inundation canals. The difference between a low Nile flood and a high one may be said to be from four to five feet, and the effect this has on the irrigation of Egypt may be gauged from the fact that it has been calculated † that the discharge of the inundation canals of Upper Egypt is about 66 per cent. greater in a good year than it is in a bad one. The Egyptian inundation canals are similar to those in India, being open channels taken off from the river without masonry head-works.

A very large proportion of the area now under irrigation in India is commanded by perennial canals taken from the large rivers. It is

* 'Note on the Prevention of *Sharaki* Land in Egypt,' by Col. Sir C. C. Scott-Moncrieff, K.C.M.G., C.S.I.

† 'Report on the Low Nile of 1888,' by Col. Justin Ross, C.M.G., R.E.

impossible to draw any very distinct line between inundation and perennial canals. There are some canals which are perennial in the sense that water does flow in them all the year round and yet the discharge is so small during the dry season of the year, as compared with that of the flood season, that they would more properly be classed with inundation canals, although that term is usually only applied to channels with an intermittent discharge. The extra depth to which such canals are cut may be sufficient to take in the water when the river is at its lowest, but the real object of it often is to increase the discharge in the season of inundation. A perennial canal may be only an inundation canal cut to a sufficient depth, but usually it has head-works in or across the river from which it is taken. One of the oldest canals * in the world, if, indeed, it is not actually the oldest now in operation, is the Bahr Yusuf in Upper Egypt. (See Plate XII., page 32.) Tradition relates that the canal was constructed by the patriarch Joseph (Yusuf) in the days of the Captivity. It was originally an inundation canal, but, after various alterations and improvements to its off-take on the Nile, it has now been made perennial by the construction of the Ibrahimiyah Canal. This canal, which is a case in point, is an open cut from the Nile without head-works or regulators of any kind in the first 38 miles of its course; it is entirely open to the floods of the river, but while other canals in Upper Egypt have their beds about 10 to 12 feet above the summer level of the river water, the Ibrahimiyah has its bed some five or six feet below the ordinary low Nile level. The discharge of this canal is probably the largest in the world: in August and September it has been known to carry 32,000 cubic feet a second. It has a bed width of about 180 feet and has a depth of about 30 feet when the Nile is in full flood. This enormous body of water is controlled by a group of six regulators at Derut, 38 miles from the canal head, where the discharge of the canal, whatever it may be, is passed into some or all of the five canals branching from the Ibrahimiyah at that point, or it is partially diverted at the same place through a large escape into the Nile again. The minimum discharge of this canal in the extraordinarily low Nile of 1889 was about 1000 cubic feet a second only, but its ordinary low-level discharge is 1600 cubic feet a second, a volume which appears insignificant compared with the full discharge of 32,000 cubic feet, but which is nevertheless just about the same as the ordinary discharge of the river Thames over the last weir at Teddington near London.

* But see page 139 of 'The Unseen Foundations of Society,' by the Duke of Argyll, concerning canals excavated by Khammorati, who reigned in Babylon before the days of Moses.

The construction of perennial canals in India was probably first instituted in Madras, where, as has already been stated, there are numerous examples of channels leading a constant supply of water from streams. In some cases, and notably in the case of the channels emanating from the Grand Anicut, as it is called, in the Tanjore district, these canals drew their supply from permanent weirs or *anicuts*, but in many cases a dam or *corumbo* was constructed across the river every year as the flood fell, to retain the water at a sufficient height to compel it to flow into the canals. These *corumbos* were often made of sand and brushwood only, and completely closed the channel of the river, diverting the entire supply into the canal.* The Grand Anicut is said to have been constructed 1600 years ago, and the Madras native engineers certainly carried out works of this kind long before anything of the sort was attempted in other parts of India. The earliest canals, in Upper India, of which any records exist, are the old canals taking off from both banks of the Jumna. The one on the west bank in the Punjab is attributed † to Firuz Shah, who, about the middle of the fourteenth century, is said to have cut a canal to irrigate his favourite hunting grounds near Hissar. The canal seems to have fallen into disrepair, but in the sixteenth century Akbar ordered its restoration; and again, early in the seventeenth century the Emperor Shah Jehan carried the canal by aqueducts and deep rock cuttings into Delhi. The Eastern Jumna Canal, on the other bank, was originally commenced by Shah Jehan about the same time as he undertook the extension of the canal on the other bank to Delhi. When the English came into possession of the country these old works were in ruins, but their restoration and improvement were very soon taken in hand. One of the earliest systems which was projected by the British after the annexation of the Punjab was the Bari Doab Canal lying in the *doab* between the Ravi and Bias rivers. There had in this case also been a small canal in the district prior to the British occupation, which was also one of Shah Jehan's works undertaken in the early part of the seventeenth century.

The earliest examples of successful perennial canals are to be found in the delta systems of Madras; of these the Cauvery ‡ or Coleroon works (Plate V.) are the most ancient, both as regards the original portion constructed by the natives, and with reference to the improvements of them which were commenced in 1836 under the supervision of

* 'Professional Papers of Madras Engineers,' vol. i. p. 80.

† 'East India (Progress and Condition), 1872-73,' printed for the House of Commons in 1874, p. 60.

‡ Ibid., p. 69.

Colonel (Sir Arthur) Cotton. The area of irrigation dependent on this ancient system, before any improvements were effected in it by the English Government, was 669,000 acres; now it is rather more than one million acres. About eighteen lakhs of rupees only have been spent on the improvements. This irrigation system is the largest delta system, and it is the most profitable of all the works in India. There are six or seven somewhat similar delta systems in Madras, and one in the delta of the Mahanuddee in Orissa, in Bengal. Of these the Godaveri system (Plate VI.) is a good example. At the head of the delta of the Godaveri the deep bed of the river is only some 8 or 10 feet below the highest parts of the delta which require irrigation, so that it was easy to command the whole area by means of a weir which was constructed across the river at Dowlaishwaram, where the total width from bank to bank is three miles and a half, but where four islands reduced the actual length of weir to about two and a half miles. The works were sanctioned in 1844. The river at the head of the delta bifurcates into two streams, which divide the area under command into three sections, each of which is watered by a canal taking off the river above the anicut (or weir) across the river. In the eastern section the main canal soon bifurcates, one branch following the high bank of the river, and the other flowing along the foot of the hilly ground bordering the delta at this part: both these branches throw off many other channels to irrigate the lower land lying between them. In the same way the canal in the central section of the delta throws off branches along the high bank of the river, which command the country between them, while one of them in its lower reaches crosses a branch of the river in an aqueduct of forty-nine arches. In the western section, the main canal divides into several branches, one of which, as in the eastern section, follows the margin of the delta, and the other follows the river bank. The main lines of canal in this system are constructed for navigation as well as for the supply of water. The area irrigated is nearly 700,000 acres.

The perennial canals of Upper India are, with the exception of the Eastern and Western Jumna Canals, which have already been mentioned, all comparatively modern works constructed by the English Government. In the Punjab, the Bari Doab Canal (Plate VII.) was commenced in 1850, partly as a measure to give employment to the large number of Sikh soldiers who had lost their means of livelihood by the annexation of the province. The head-works of the canal are on the Ravi near Madhopore, where the river emerges from the hills, and where it has a minimum

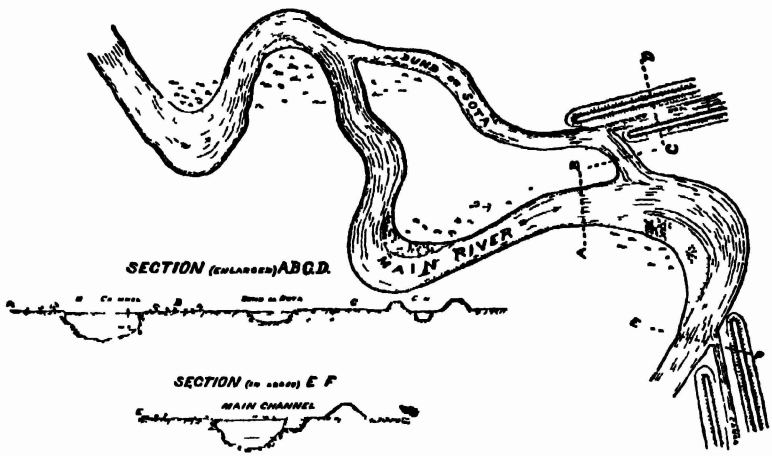
discharge of 1200 cubic feet a second, which can be diverted by the weir across the river into the canal. The maximum discharge of the canal has been 4000 cubic feet per second, and the area irrigable is 525,000 acres; of this 523,000 have been actually irrigated. The nature of the *doabs* of the Punjab rivers has already been explained (page 9); in this case the main canal is carried down the centre of the high land, and numerous branches are thrown off which command the greater part of the upper portion of the tract lying between the Ravi and the Bias. The system consists of 354 miles of main and branch canals, and over 1000 miles of distributaries. The Sirhind Canal (Plate VIII.) is one of the most modern of the large perennial systems; it emanates from the Sutlej near Roopur, in the Umballa district of the Punjab, at the point where the river issues from the Siwalik Hills, and irrigates portions of the British districts of Loodiana and Ferozepore, and of the Native States of Puttiala, Sheend, and Nabha. There is a masonry weir across the river, and a regulating sluice at the head of the canal, which takes off the left bank of the river: the minimum discharge of the river is said to be 2800 cubic feet a second; the maximum discharge of the canal is 6000 cubic feet. The construction of the works was commenced in 1869, and they were first brought into operation in 1882; the area irrigable is 522,000 acres in British territory, and 278,000 acres in Native territory. In addition to these two perennial systems there are five or six others of smaller magnitude in the Province of the Punjab.*

In the North-Western Provinces, the Ganges and Lower Ganges Canals are the two principal perennial systems (Plate IX.); both of these take off the right bank of the Ganges, the Lower Ganges Canal by means of a weir built across the bed of the river, and the Ganges Canal by the help of temporary embankments of rubble stone, fascines, and earth, which are annually made after the subsidence of the floods, and annually destroyed when the floods rise.† In the tract commanded by the Ganges Canal, cultivation was formerly almost entirely dependent on wells, but near the village of Rampore, there is said to have been an old canal from the West Kali Nuddi about 12½ miles in length, which is supposed to have been constructed by Muhummud Aboo Khan to irrigate groves and gardens in the neighbourhood of Meerut. Traces of this canal still exist. The Ganges Canal consists of 440 miles of main and branch canals and 2600 miles of distributaries, and the Lower Ganges Canal has 560 miles of canals and 2000 miles of distributaries. The area irrigable by the former is 1,600,000 acres, and by the latter 1,190,000

* See statement on page 276.

† See page 131.

be made at some point such as B C, and the entire discharge of the dund forced into the canal. In that case the silting of the channel would be greatly increased, and the length above B C would silt up more rapidly. When the lower end of the dund is open the amount of deposit would be much less, but it is then doubtful whether the amount of silt in the canal at C D would be greatly less than in the case of the canal at E F, which is drawn directly from the main channel of the



OFF-TAKE OF INUNDATION CANALS

river, provided that the level of the bed was the same, and that the bank of the river above the canal head was a stable one A canal taken off on a cutting bank or immediately below a cutting bank is soon choked with silt. These remarks apply mainly to rivers such as the Indus and the Nile, which carry a preponderance of earthy matters in suspension in the waters But where a river carries a large proportion of sand in suspension, and which has, therefore, a higher velocity than one which carries finer matter, an advantageous way of constructing a canal, with the view of excluding the heavier sandy silt, would be that shown by the canal at C D: a masonry escape might be constructed at B C and a head regulator built to the canal, say at the line C D, through which the supply should be regulated so as to draw the water as far as possible from the surface of the stream. This can be done by combining the system (see p. 186) of horizontal and vertical regulating baulks, the lower portions of each vent in the regulator being closed by horizontal baulks and the supply regulated above them by verticals.

The native rulers, who originally constructed most of the inundation canals in India, appear to have learnt from experience the necessity of selecting spots for the heads of the canals which were screened from the full force of the current during the inundation. The experiments made by Colonel Tremenheere, R.E.,* show that—

(1) Those inundation canals of Sind, which draw their supply from branches separated from the main river by islands covered with brushwood and long grass, contain a comparatively small amount of material in suspension. The brushwood and grass impede the velocity of the water and clarify it.

(2) That canals having their heads in the main stream where the velocity is normal may be expected to contain silt to the extent of $\frac{1}{300}$ by weight, and that about one-third of this quantity is ordinarily deposited in the canals.

(3) That canals having their heads on the main stream in a part where the channel is restricted and the velocity increased may contain silt to the extent of $\frac{1}{200}$ by weight, of which half may be deposited in the canal.

These points have always to be considered in selecting a site for the head of an inundation canal, and they explain why a favourite site is a little way above the point where the lower end of a *dund* joins the main stream, for if, as is often the case, the dund ultimately silts up at the head, a backwater is formed at the lower end, from which water can be drawn which is comparatively free from the heavier silt. But such a head would only be a temporary one, as a rule, for the backwater would sooner or later become filled up by deposit.

Colonel Justin Ross, who was Inspector-General of Irrigation in Egypt, found that the old inundation canals of the Nile were usually† aligned by the Arab engineers on the following principles :—

(1) The offtake should be placed in the bank along which the deep water of the Nile flowed, and the canal axis should be, as nearly as possible, a tangent to the general curved sweep of the central current of the reach of the river in which the canal lay. The natives altered the heads of some canals, at great expense, in order to fulfil this condition.

(2) When a canal had to be taken from a straight reach of the Nile, it should be taken at a very acute angle to the axis of the river.

(3) That a canal head should not be placed at a point where a sand-

* 'Roorkee Professional Papers,' 1st series, vol. iii. p. 25.

† 'Notes on the Distribution of Water and the Maintenance of Works in Upper Egypt,' by Lieut.-Colonel Justin C. Ross, C.M.G., p. xxiii. Cairo, 1892.

bank was forming. The coarse sand, which rolls along the bottom of the Nile bed, does not enter the canal unless the bed of the river has become silted up to nearly the level of the canal bed. This coarse sand is the most fatal to permanence of supply, as it falls in the head of the canal and chokes the discharge.

The rise and fall of the Punjab rivers in the neighbourhood of the inundation canals is commonly about 8 feet, but sometimes 10 or 11 feet, above the lowest or winter level of the river. The rise and fall of the Indus at Sukkur, which is above the heads of the majority of the Sind

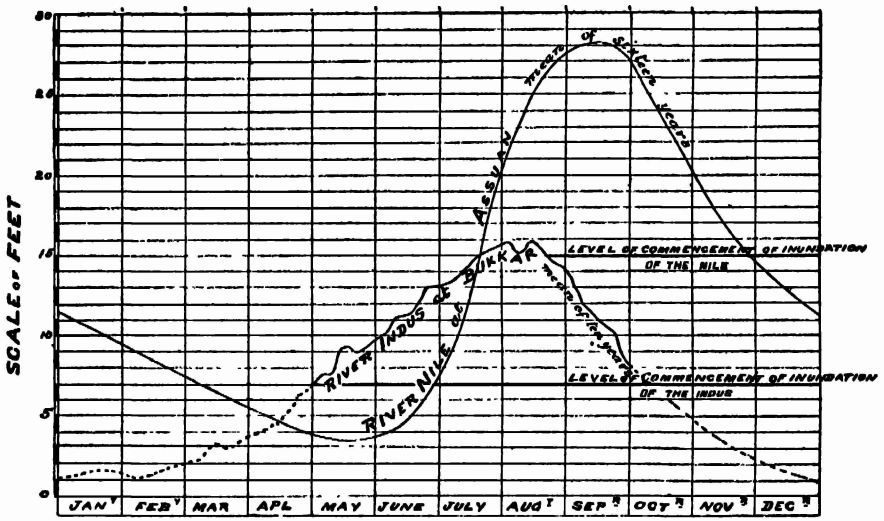


DIAGRAM OF ORDINARY FLOODS IN THE INDUS AND THE NILE.

inundation canals, is about 15 feet, and at Kotri, about 280 miles below, the rise and fall is slightly less. The diagram on this page shows the ordinary rise and fall of the Indus at Sukkur. The velocity of the stream, in most parts of the river, is greater than the nature of the banks can stand, and the heads of some of the inundation canals have to be cut afresh each year. The Punjab inundation canals vary in width from 6 to 50 feet,* and in length from 8 to 60 miles. The depth of water in them ordinarily during the inundation is about 5 to 8 feet only, according to the depth of their beds and the nature of the flood; but in some canals it is at times as much as 10, or even 12 feet. The bed slope of the canals is sometimes as much as $\frac{1}{4000}$ (= 0·25 per

* 'Roorkee Professional Papers,' 3rd series, vol. iv., Inundation Canals, by E. S. Bellasis.

thousand), and rarely less than $\frac{1}{10000}$ (= 0·10 per thousand). The beds of the canals are nearly always in soil, but the water surface is generally kept above ground-level a few miles from the head. In these respects the inundation canals of India differ essentially from those of Egypt. The latter rarely, if ever, have a more rapid slope than $\frac{1}{20000}$ (= 0·05 per thousand), and there are some as flat as $\frac{1}{33333}$ (= 0·03 per thousand), while the water in them is almost always kept below, or only very slightly above, the ground-level, mainly on account of the great porosity of the soil. The difference in slope is partially explained by the difference in the slope of the country, the valleys of the Punjab rivers having a slope of about $\frac{1}{5000}$, while that of the Nile valley is about $\frac{1}{10000}$. Some of the Indian canals are provided with regulating bridges or stop dams, which control the discharge in high floods: they are usually situated at some distance down the channel, in order to protect them from being cut away by the river. The discharge is checked by baulks placed in grooves in front of the regulator, which pond up the first reach and reduce its slope. One almost certain effect of this system of regulation is an immense increase in the silt deposit. Other canals are supplied with two separate supply channels, one being kept closed during the height of the flood, and opened when the first has silted so much as to diminish the supply below the requirements. The canals are generally very tortuous, and were aligned more with reference to the requirements of individuals or villages than with reference to the best manner of irrigating with economy.

The inundation canals of the Punjab commence to fill with water about the end of April or beginning of May, and run dry about the end of September. During the earlier months, before the flood has risen sufficiently, lift irrigation is practised. The superiority of the river water over that of wells is demonstrated by the fact that near the heads of the Punjab canals the cultivators prefer to pay canal rates and to lift the water from the canals rather than to lift it from wells, although the canal level and the spring level are about the same. When the flood has risen sufficiently, the autumn or *khareef* crops of rice, bajra, jowar, cotton, indigo, &c., are irrigated by flow, and, at the same time, considerable areas of fallow land are flooded, with the double object of manuring the land by the silt deposit, and of saturating it so that sufficient moisture may be retained in the soil to mature the *rabi* crop. This crop consists mainly of wheat: it is grown after the rivers have fallen too low to command the fields. In this respect the irrigation from these inundation

canals is similar to the "basin" system of Egypt, which will presently be described, but it is not conducted on nearly so large a scale, nor so methodically and efficiently. In the Punjab the crops which are grown, mainly by flow irrigation, during the time of the inundation (*khareef* crops) are greater than those (*rabi* crops) which are grown after the subsidence of the rivers on fields which have been moistened during the inundation, in the proportion of about 5 to 4; the area cultivated with the latter crop is about 450,000 acres. It not unusually occurs that the inundation of the rabi lands is not sufficient to entirely mature the crop (as it does under the "basin" system of Egypt), and that the fields are watered to some extent from wells after the inundation canals have ceased to run.

In Sind the crops grown mainly by direct flow from the inundation canals, during the period of the inundation, bear a far larger proportion to the entire irrigation than is the case in the Punjab, the area under these crops being about seven times as large as that under the cold weather (rabi) crops. The crops in Sind are chiefly jowar, bajra, and rice, the area under these three crops alone being nearly nine-tenths of the total extent of the irrigation (about 1,700,000 acres). In Sind the proportion of land irrigated by lift is much greater than in the Punjab, the canals being generally in lower ground and more in soil. The Sind inundation canals are larger than those in the Punjab; there are seven or eight which carry between 1000 and 4000 cubic feet a second on the average, and one, the Fuleli Canal, which averages nearly 8000 feet in ordinary years.

The inundation canals of Egypt are to a certain extent used, as those of India mainly are, for the irrigation of standing crops, but this is only the case to a comparatively small extent: in India a large percentage of rice requiring a copious supply of water is grown under the irrigation of inundation canals, but in Egypt, rice is rarely grown except on the inferior lands or on lands which contain too much salt to be suitable for the better and more valuable crops. The crops which are standing in the fields during the period of the Nile floods are chiefly sugar-cane, maize, and vegetables grown on the *sahil* lands, which are the higher lands on the margin of the river. These crops, which are called the *nabari* crops, form in some districts an important and valuable part of the cultivation, but they only cover a small percentage of the Nile valley which is irrigated during the inundation. In many cases these nabari crops are irrigated by lift. The water which the Egyptian inundation canals draw from the annual flood of the Nile, is principally

used for saturating the ground during the inundation (August to October) in order to provide moisture in the soil for the crops grown during the winter months (November to March), but also for the purpose of enriching the land by an annual deposit of the red mud which is held in suspension in the waters of the Nile. It is hard to say which of these two processes is the more important. There are (with one exception) no perennial canals commanding the lands in Upper Egypt, above Cairo, and as, even if there were, the supply in the Nile during the greater part of the year is not sufficient for the irrigation of the standing crops, and as the rainfall is practically nothing, it is necessary to supply the land with moisture during the time when the floods in the river are high enough to command the country. But this alone is insufficient. Experience has shown that if the lands are cultivated with water which does not contain the rich silt of the flood season, they rapidly deteriorate, and that the frequent deposition of Nile mud on the lands is essential to high cultivation. Hence the system known as the "basin" system has been employed from time immemorial for the irrigation of lands from the inundation canals. This system may be briefly described as one under which the area irrigated is divided by embankments into a series of large shallow tanks or "basins," and each "basin" is filled with Nile flood water to an average depth of about three feet. The basins commence to fill about the 15th of August and are generally filled up to the highest level by the 25th of September. It may be said that the water lies in the basins for about one month, and is then drained off into the Nile again as the floods subside: during the time the water lies on the land it saturates it, and deposits a thin slimy coat of Nile mud. When the water commences to drain off the land the cultivators wade about, up to their ankles, or deeper, in mud, and mark out afresh the limits of their respective fields; then, within five days after the water has left any particular field, the seed is sown and the cultivator has done his work until the crop is ready to cut. The fields irrigated under this system are not ploughed except for wheat, and not always in that case, but wheat gives a better return on ploughed land.

Before the Egyptian system of inundation canals can be understood it is necessary to refer briefly to the lie of the land in the valley, and to the nature of the Nile floods. The river between the first cataract at Assuan and the head of its delta at Cairo, winds backwards and forwards in a valley which is defined by the steep cliffs of the desert. This valley averages about four miles in width but varies from fifteen miles in the broadest part to nothing at all at several points where the

desert touches the river on both banks. The length of the course of the river from Assuan to Cairo is 584 miles, and the length of the axis of the valley is about sixty miles less; the slope of the river surface is about 0·075 to 0·08 per 1000, and that of the surface of the ground on the line of the axis of the valley about 0·09 to 0·10 per thousand. The slope of the beds of most of the inundation canals is 0·04 per thousand; so that, if a canal is taken from the river in the direction of the axis of the valley, the water surface of the canal would gain on that of the ground at the rate of about 0·05 to 0·06 per thousand. Or in other words, if the Nile flood were one foot below the level of the ground, the water could be delivered on to the surface by a canal in about 18,000 to 20,000 feet. But the Nile, like all rivers which have gradually raised their beds and banks by overflow and deposit, runs in the higher land, so that a cross-section of the valley, taken at right angles to the river, would show that the land slopes very gradually from the river towards the desert cliffs on either side. The canals cannot, of course, always be taken off from the river in the direction which would ensure the earliest possible delivery of the water on the surface, but taking the slopes in both directions into consideration, it may be assumed that an inundation canal in Egypt will gain on the surface of the land at about 0·05 per thousand.* This is a low rate, and it displays at once the extreme importance of the height and duration of the annual flood, for each difference of 0·05 feet in the level of the flood at the head of an inundation canal means that the water reaches the surface of the land 1000 feet lower down the channel, and it means also a perceptible reduction in the discharging capacity of the canal.

The floods of the Nile are extremely deliberate in their behaviour; they rise with great steadiness, and although there are flushes in the river during the period of flood, these flushes are far less violent than on some Indian rivers. The floods are so regular in their flow that it is possible to predict the level of the flood with great accuracy, at any point of the river when the level at any other point of it is known. It is usual to speak of the floods with reference to their level on the old Ptolemaic gauge at the first cataract at Assuan which is divided into the old graduations of *pics* and *karats*.† Thus a flood which has reached ten pics on the Assuan gauge is known as a ten pic flood all down the

* Col. Justin Ross, C.M.G., in his 'Report on the Low Nile of 1888,' gives in page 64 a table which shows that the average gain of 24 canals is about 0·046 per thousand.

† One pic = 24 karats. A pic = 0·54 metre = 21·26 inches.

valley, and the level which it will reach at all points is well known. So much is this the case that it is the custom to speak of an inundation canal as having its bed at 8 pics, 10 pics, 12 pics as the case may be, by which it is meant that the bed of the canal is such that, when the river rises to 8, 10, or 12 pics at Assuan, it will just flow into the bed of the canal in question. The Nile floods are usually divided into "High" Nile, "Mean" Nile, and "Low" Nile, according to the levels at Assuan. During the thirty years ending with 1889 there have been six years of "Low" Niles, seventeen years of "Mean" Niles, and seven years of "High" Niles. A "High" Nile is one which rises up to (16 pics 4 karats) 28·6 feet on the Assuan gauge; a "Mean" Nile one which rises to (15 pics 10 karats) 27·3 feet; and a "Low" Nile to (13 pics 19 karats) 24·4 feet. The abnormally bad flood of 1877 only reached (13 pics) 23·0 feet, and the abnormally high flood of 1874 reached (18 pics 4 karats) 32·1 feet. The year 1877 was disastrous from drought: the year 1874 from devastating floods. The difference between an ordinary "Mean" Nile flood and a "Low" Nile is about three feet, but this difference, as has been just explained, means that the water in an average inundation canal will be delivered at the surface about 60,000 feet lower down the canal in a "Low" Nile than it would in a "Mean" Nile. This result is disastrous unless measures are adopted for passing water forward, from a canal taking off still higher up the river, on to the area which the lower canal has failed to command.

The rise and fall of the Nile at the First Cataract is about three feet greater than it is at the head of the delta at Cairo; the difference, consequently, between a "high" Nile and a "low" one is greater in the higher reaches of the river than it is in the lower reaches, and the proportion of land thrown out of cultivation owing to a low level of the flood of any particular year, is therefore greater in the upper parts. It has already been said that, at some places, the desert cliffs, which border the valley of the Nile, approach close up to the river. These points are known as "Mahgars"; in some of them the cliffs are of rock, which stands perpendicularly over the river, and it is impossible to carry a canal past them at any reasonable cost: in others there is a gravelly slope leading down to the water on which a canal can be constructed. Plate XI., Fig. I., shows a small tract of country, lying between the "Mahgars" of Gebel Tukh and Gebel Haridi, which exemplifies the old and faulty system under which the inundation canals failed to command the country when the flood was not a high one, and Fig. II. shows the new system which has been introduced under the direction of Colonel

Justin Ross, C.M.G.* This tract of country is about 25 miles long by 4 or 5 miles broad, and it is divided into five main "basins" or Hods. The Hod Akhmin at the upper end is 7269 acres in extent; the Hod Sawamah is 3942 acres; the Hod Tawayi is small; Hod Kitkatah is 4678 acres, and the Hod Galawiyah is about 2500 acres. The Hod Akhmin, it will be noticed, is supplied by the Lahaywah Canal, which is carried round the "Mahgar," but the other basins, Fig. I., used to be supplied by the Issawiyah, Saqultah, and two other smaller canals, which take off from the river in the immediate vicinity of the basins. There was no channel leading round the lower "Mahgar" of Gebel Haridi, and the upper basin of the tract of country below that point used to rely only on the canal (the Khizndariyah) taking off the river in the vicinity. The irrigation of this tract—that is the filling of the basins with about 3 feet of water—might have been effected in a "high" Nile, that is one rising to 28·6 feet at Assuan, but in a "low" Nile, which would be 4 feet lower, the amount of water entering these short canals was very small and the level of it was too low to do more than make a few pools perhaps in the lower parts of the basins, and the Galawiyah Basin probably received no water at all from the very short channels leading to it. The upper basin—Akhmin—would have been better supplied by the longer canal leading round the Mahgar, which is carried in syphon under the Issawiyah Canal and commands the area just below the Mahgar which was not (except in extremely exceptional years) irrigated by the Issawiyah.

Fig. II. shows the new system. The Lahaywah Canal has been extended and made to supply the Sawamah Basin. The Issawiyah Canal is not only extended all through the tract of land between the two Mahgars, but it is carried round the lower one and is passed, in its turn, in syphon under the Khizndariyah Canal for the supply of the higher land of the lower tract below the lower Mahgar. The extensions of the Issawiyah Canal have been aligned to utilise as far as possible the lines of the old canals. This alteration in the system gives to the lower basins, Tawayi, Kitkatah, and Galawiyah, a supply which is drawn from the river by the Issawiyah above Akhmin, instead of one drawn from the river immediately opposite the basins, and the higher basins of the next system, below the Mahgar of Gebel Haridi, are also supplied from the same canal, so that a much better supply can be passed into them.

* 'Report on the measures to be taken to prevent Sharaqi in Upper Egypt,' by Col. Justin Ross, C.M.G.

Indeed, in a bad year the greater part of this area was formerly hardly watered at all.

The system which is sketched in Plate XI. is a very small one, but it is a good exemplification of the basin system of Upper Egypt. The basins are filled gradually on the rising Nile about 8th to 18th of August, and the water is retained in each basin at the proper level, which gives about 3 feet of water over the surface of the ground, by means of regulating bridges placed in the dividing embankments (see p. 185). When the Nile begins to fall, about the middle of October, the water is gradually drained off from the lower basins back into the river, and the lands are ready for cultivation with a rich deposit of red Nile mud upon them. In the particular case shown in Plate XI. there is a masonry inlet from the Galawiyah Basin into the Issawiyah Canal, and a masonry escape from the canal into the river. This arrangement permits of some of the water from the Akhmin system of basins being passed forward into the lower system, if it happens to require a larger supply than it has obtained from the direct flow of the Issawiyah Canal. In many of the groups of basins this method is employed to "top up" the lower basins to their full irrigation level; but the water, which is thus passed forward from one group of basins to another, is by no means equal in quality to that supplied directly by the canals. For, in the latter case, the water will contain a much larger proportion of silty matter than is the case with the water which has passed through a series of basins and has had time to deposit its fertilising matter on the fields.

The original system of draining a series of basins was simply to cut the lower bank of the lowest basin of the series, and to allow the water to drain off into the Nile as the level of the river fell in October. But this system was not advantageous to the cultivators, and several large masonry escapes have been recently constructed, and all the systems will eventually be supplied with them (see p. 188). It is most desirable that basins should be drained at a moderate rate, so that the cultivators may have time to sow the seed in the slimy mud deposited by the Nile. If this mud is once allowed to harden, great labour in ploughing and watering is necessary before it can again be brought into a condition to receive the seed. The system of drainage by open cuts into the Nile left the rate of draught, of the lower basin at any rate, and of all the series to some extent, entirely to chance. It occasionally happened that the Nile flood was at a convenient level at the time the cut was made, and that the drainage was consequently effected at convenient speed. But this was not always so. At times the river would fall too rapidly, and the dis-

charge would be far too sudden: the annual cost of making up the banks again with earthwork, where they had been cut away by this system, was considerable. The masonry escapes are doubly useful, for they are not only used to drain off the water after the inundation is complete, but in years of high Niles they can be used to admit the early red water direct into the lower basins from the river, and, later on, to keep up a through flow of red water in the chain of basins. In years of extremely high Niles, when the water rises over the bank of the river along its entire course, any basin could, of course, be filled direct from the river, and most of them could be filled, even from their lower ends, to a foot or more above their ordinary full supply level. So an escape at the end of a system can be used to fill the lowest basin, and a portion even of the one above it: and this can in most cases be done without injury to the lower basin; for, in Upper Egypt, the lowest basin has generally been over filled in years of high Niles by the surplus waters of the upper ones, and the houses and banks in it are usually particularly well raised.

It will be noticed that in the Akhmin series of basins (Fig. II. Plate XI.) the Issawiyah Canal, after it has passed the Sawamah Basin, follows more or less the higher land on the bank of the river. Many of the older inundation canals followed the more easy alignment near the foot of the desert cliffs. It is obviously an advantage to follow the higher land when possible: for, when the supply of a basin is effected from a canal in the low ground, the water as it gradually rises, inch by inch, at the rate perhaps of about one or two inches only a day, deposits the greater proportion of the silt in the immediate vicinity of the canal, and the higher lands receive in the end, when the basin is full, water which has less fertilising properties. But when, as in the example, the basins are filled from the higher levels a much more equitable distribution of the silt is obtained. As the slope of the land, both in the direction of the axis of the valley and from the Nile towards the desert, is very regular, the corner of a basin which is nearest the river, and which is on the southern end of the basin, is always the highest point in it. These high corners are frequently divided off from the main basins by small embankments, and cultivated by lift at the time when the basins are under water: on the banks of the river also the highest land is regularly cultivated in the same manner. A study of the floods of the Nile shows that the best red water—that is the most fertilising water—is furnished by the floods of the last days of August,* and that the flush

* 'Report on the Low Nile of 1888,' by Col. Justin Ross, C.M.G. Cairo, 1889.

in the early part of September is charged with red silt to the extent, it is believed, of only 36 per cent. of the amount held in suspension in August. The basins which receive the early red water are celebrated for their yield, while the minor basins on the higher lands which get water later are visibly inferior, and the selling price of the land is low. The importance of the red water may be inferred from the fact that where it is brought straight on to higher lands which have not before enjoyed a direct supply, the yield is increased by upwards of 500 lbs. per acre.* The improvements which have been described, not only protect the lands in Upper Egypt from drought in extreme low Niles, but the increased supply in good years, and the alignment of the new canals, allows of the early red water being carried into the upper parts of the basins, so that after a few years the impoverished land should be brought up to a high state of cultivation.

The inundation canals of Upper Egypt vary in size from little channels having their beds at twelve *pics* (that is with their beds at such a level that a flood of 12 pics or 25½ feet on the Assuan gauge will just enter them), and bed widths of 13 feet up to the Suhagiyah Canal,† which has its bed at 8 pics (14·2 feet), and a bed width of 328 feet. The great majority of the canals have their beds at 8 and 9 pics. A canal with an 8 pic bed would (see p. 26) run with a depth of about 10¼ feet in a "low" Nile, of about 13 feet in a "mean" Nile, and of about 14½ feet in a "high" Nile, and if the discharge during a "low" Nile is taken as unity the discharge in a "mean" Nile would be about 1·6, and in a "high" Nile about 2·00: but these proportions would vary of course with the hydraulic mean depth of the particular channel. The table‡ on the next page gives statistics of a few of the inundation canals of Upper Egypt.

But the largest of these is small compared with the Ibrahimiyah Canal, which supplies the provinces of Assiut, Minia, and Beni Souef in Middle Egypt. The system of basins in these provinces is the largest and, in many ways, the most interesting in Egypt, and the Ibrahimiyah Canal, which supplies them, is believed to be by far the largest inundation canal in the world. This canal may be properly classed as an inundation canal; for, although it is actually a perennial canal as it has its bed about 6 or 8 feet below ordinary low summer Nile, and has an ordinary

* 'Report of the Administration of the Egyptian Irrigation Department, 1890,' p. 5.

† The Ibrahimiyah Canal, which has a larger discharge, is lower down the river, in Middle Egypt.

‡ 'Report of the Administration of the Egyptian Irrigation Department, 1890,' p. 63.

INUNDATION CANALS OF UPPER EGYPT.

Name of Canal.	Bed Width in feet.	Bed Level in *pics.*	Slope of Bed per thousand.	Discharge in "Low" Niles in cubic feet per second.	Discharge in "Mean" Niles in cubic feet per second.	Area commanded in acres.
Ramadi	65	8	0·04	1,150	1,860	24,270
Fadiliyah	39	8	0·04	700	1,150	14,689
Kasrah	69	8	0·04	1,200	1,960	39,090
Suhagiyah	328	8	0·05	8,100	12,350	?
Killabiyah	23	10	0·03	270	370	11,518
Ghilasi	52	8	0·04	925	1,510	33,517
Khizndariyah ..	59	8	0·05	1,160	1,890	28,917

minimum discharge of 1600 cubic feet* a second; still, its main function is to carry the waters of the high Nile in the flood season to inundate four groups or series of basins which have an aggregate area of nearly half a million acres. At the same time this great canal commands an area (exclusive of basins) of about 227,000 acres of higher lands, the greater portion of which is cultivated with crops of sugar-cane, cotton, vegetables, and summer maize, which are irrigated by the perennial supply of the canal during the summer months (March to July), when the river is low and when ordinary inundation canals are dry. This class of cultivation is known in Egypt as *sefi*, and the crops are grown on the higher lands in the neighbourhood of the river, or on the higher portions of the basins which have been excluded by embankments from the annual submersion.

The Ibrahimiyah Canal (Plate XII.) was constructed by Baghat Pasha, and was completed about the year 1873. Before that time the higher lands were irrigated during high Nile—August to October—by flow, when the river rose high enough to command them, and if not, by lift from the canals or from the Nile itself: they did not then bear the large tracts of sugar-cane and other crops which require irrigation in the hot months of April, May, and June. Before the construction of this canal the basins, which are now mainly supplied by it, were supplied directly from the Nile and by the Bahr Yusuf, and at that time they extended closer to the margin of the river than they do now, the old transverse banks are still traceable in many places. The supply of the basins was

* But it fell to about 900 cubic feet in the extraordinarily low summer Nile of 1889.

then drawn from the river by a number of smaller inundation canals which were closed when the Ibrahimiyah Canal was made. The basins were, at first, supplied only from that canal and at about the same time the area under basin irrigation was reduced by the construction of an embankment on the left side of the canal, and more or less parallel to it, which formed a new boundary for the basin systems. The construction of the Ibrahimiyah Canal was, at first, very deleterious to the basins which lie below the point where the Bahr Yusuf, which is a very old canal of great capacity, takes off from the Ibrahimiyah Canal. The basins above that point were well supplied with red water from the Ibrahimiyah ; but, below that point, the basins had to be fed from the Bahr Yusuf which runs in the lower ground, and, consequently, as has already been explained (p. 29), the higher lands, which had formerly received a supply of silt laden with red water direct from the Nile, now received water which had, to a considerable extent, deposited its fertilising qualities. The land, on the other hand, which was placed under perennial irrigation from the new canal, increased greatly in value, and the cultivation of sugar-cane in huge fields, extending in an unbroken line for miles, made a great advance. This mistake of shutting off the direct feeders from the Nile has now been rectified to a large extent by the construction of new feeders or the reopening of old ones from the Nile and from the Ibrahimiyah Canal ; these feeders will be found on the plan (Plate XII.)

During the period of the Nile inundation the depth of water in the upper reach of the Ibrahimiyah Canal is about 33 feet, the canal has an average bed width of about 200 feet, and a surface slope, at that time, of about 0·08 per thousand (1 in 13,000): its maximum discharge has been over 32,000 cubic feet a second. The canal is quite open to the river at its head and there are no means of controlling the discharge entering it. The first regulation work is at Derut where a maximum quantity of 26,000 cubic feet per second can be drawn off the canal into various branches and where the remainder, whatever it may be, must be passed into the river again by a large escape. This regulator at Derut is a remarkably fine work in masonry.

There are four groups or series of basins which are mainly supplied from this large inundation canal. The first or Assiut series commences with the Hod Malah (2972 acres) and ends with the Hod Itqa (8500 acres). The supply to these basins is given entirely from the Ibrahimiyah Canal, except that to the Hods Malah and el Masrawi which is given from the series of basins lying above it. The water, which is here well charged with silt, is passed on to the upper parts of the basins as

shown in the plan by blue arrows, and the depth of water in any particular basin is controlled by the masonry regulators in each bank. When the Nile falls the water is drawn off as shown by the black arrows into the Bahr Yusuf through the Dalgawi masonry escape (fifteen openings of nearly 10 feet each) on the left bank of that channel in the lower part of the Hod el Dalgawi (50,000 acres), and the discharge of the Hod Tanuf and Ashmunin passes either through the Hod Itqa, where there is no embankment on the Bahr Yusuf, or into that channel direct.

The second or Minia series of basins commences with the Hod Tahnashawi (36,749 acres) and ends with the Hod Salaqus (5500 acres). It is fed at one point from the Ibrahimiyah Canal, and at another, just above the village of Qulosnah, from the Nile direct. The drainage of this series is effected partly by cuts made in the banks of the upper six basins on the margin of the Bahr Yusuf.

The third series of basins lies between the Bahr Yusuf and the desert cliffs. It is really hardly a basin system at all, as there are very few embankments and it is often insufficiently supplied; it consists of land which is inundated when the level of the water in the Bahr Yusuf is sufficiently high to command it. The water flows on to the land and from it according to the levels in the Bahr Yusuf.

The fourth or Beni Suef series of basins commences with the Hod es Sultani (25,523 acres) and terminates in the Hod Qushesha (80,446 acres) which is the largest basin in Egypt. It is fed direct from the Nile at four points by inundation canals or feeders, three of which pass in syphon under the Ibrahimiyah Canal, and it is fed at one point from that canal direct. When the Ibrahimiyah Canal was first made it was carried beyond the point where it now ends, but it was found that this series of basins, and especially the great Qushesha Basin, was suffering so much from want of red water, that the canal was curtailed and the end of it converted into an inundation canal, or feeder, to bring in water direct from the Nile. The discharge from this series of basins passes, as shown by the black arrows, through regulators in the dividing embankments, into the Qushesha Basin: this immense basin also receives, as the drainage of all the basins proceeds, all the water which has been collected in the whole of the other three series and which passes down the Bahr Yusuf: so that the drainage of all the four series passes into the Nile at the tail of the Qushesha Basin. Some small quantity is, however, sometimes passed on to the next lower basin which has a separate escape into the river.

The escape at Qushcsha, by which the whole area (nearly one thousand square miles) is drained into the Nile, has hitherto been worked by an embankment only. A masonry escape, of 60 vents of rather less than 10 feet (3 metres) in width, was completed in 1891 (page 189). The system which was previously employed was to make up the embankment across the drainage channel leading into the Nile before the flood season, and to cut it in October when it was necessary to drain off the impounded water. To a certain extent it was possible to regulate the discharge at the beginning of the drainage, for a portion of the embankment was made of rubble stone, and there are large quantities of rubble in the enormous hole which has been scoured out below it: so, by removing the crest of the rubble bank, water could be run off the surface of the basin, and this was done to a considerable extent in 1890, the top of the rubble bank being gradually removed and the water allowed to pass over it. The system of discharging all the four series of basins simply by cutting an embankment, was very unsatisfactory, both because the bank was liable to breach at times when drainage was not required, and because there was no possibility of regulating the discharge after the bank had once been cut through. The quantity of water which passed through this open cut into the river was enormous, as may be estimated by the fact that the masonry escape which has now been built, has a maximum discharge of about 80,000 cubic feet a second: the discharge through the open cut must at times have been much greater than this; it was sufficient to raise the level of the Nile considerably, and the flush caused by it was counted upon in Lower Egypt for the final irrigation of certain areas. In 1884,* a year of low Nile, the cutting of the Qushcsha dam raised the level of the Nile more than 4½ feet at Cairo in thirty hours, representing an increased discharge of 90,000 cubic feet a second. The artificial flood created by this means will be also produced by the action of the new masonry escape, which has been designed to fulfil the same object.

* 'The Qushcsha Basin Escape in Middle Egypt,' by Major R. H. Brown, R.E., Inspector of Irrigation in Egypt, 'Professional Papers of Corps of R.E.,' 1892.

CHAPTER III.

SILT.

Nature of Silt—Proportion of Silt in different Rivers—Quantity of Material carried to the Sea by the Indus and the Nile—Shingle Deposits in the Ganges and Jumna Canals—Heavy Silt Deposits in Sone Canals—Sand carried into the Canal by Flow along the Bed—Proposed Method of treating Cases of heavy Silt—Comparison of Silt in the Sone and Sirhind Canals—Flushing out Silt in Canals of Upper India—Silt in Egyptian Canals—Canals choked by Drifting Sand—Brick and Stone Groynes to prevent Silt—Silting checked by uniform Velocity.

THE silt which is borne in suspension in the waters of rivers, consists of organic and mineral matters, which, while they are often a source of abundant advantage to the fields, are, not infrequently, the cause of much trouble in the channels of irrigation works. It is desirable in all cases to pass forward to the fields as much fertilising material as possible, but it is also desirable to prevent the deposition of the silt in the channels, where it impedes, and sometimes completely chokes, the discharge.

Silt varies enormously in its nature, according, generally speaking, to the velocity of the river which carries it and to the character of the catchment area of the river. Thus, in the canals taking off the Ravi, the Jumna, and the Ganges, near the points where these streams first debouch from the hills, and where the fall of the beds is from 10 to 19 feet in a mile, and the velocities are as great as from 10 to 15 feet a second, the matters which are occasionally swept down to impede and sometimes to block the channels consist mainly of shingle and boulders. Lower down the courses of these same rivers and other similar ones, shingle and boulders give place to coarse sand mixed also with mud, carried by velocities of perhaps 5 to 8 feet a second, at surface slopes of 1 to 2 feet a mile: and nearer the sea, where, as in the case of the Nile in Egypt or the Ganges in Bengal, the surface slope of the floods is from 5 inches to as little as 3 inches a mile, the silt consists of the finest sand mixed with a large proportion of mud, borne by a stream

flowing with a velocity of only 2 or 3 feet a second. This silt when deposited is a soft slimy mud of a highly fertilising nature.

Unfortunately very imperfect records exist of the amount of silt carried in suspension by rivers. The experiments of Messrs. Humfreys and Abbot on the Mississippi show that the amount of silt increases slightly according to the depth from the surface of the river: the silt at the bottom being about 6 per cent. greater than at the surface in the case of that particular river, which is one of the moderate velocity of 4 feet a second or less.* In rivers of greater velocity it is probable that the difference may be greater, but this is a point on which little evidence has been recorded. According to M. Surell's researches on the Rhine, which has a flood velocity of about 8 feet a second, the silt at the bottom is as much as 88 per cent. greater than that at the surface. There is more silt in a rising flood than in a falling one, and the maximum amount of silt is not, apparently, carried when the flood is at its maximum, but when it has risen about two-thirds of its height. The following table shows the maximum amounts of silt found in various rivers:—

Name of River.	Approximate Velocity.	Experimenters.	Proportion of Silt to Water by Weight.
	feet per second.		
Mississippi ..	..	Humfreys and Abbot ..	$\frac{1}{572}$
Rhone	8	Gorsse and Subours ..	$\frac{1}{45}$
Po	..	Lombardini	$\frac{1}{300}$
Vistula ..	10	Spittel	$\frac{1}{48}$
Rhine	..	Hartsoeker	$\frac{1}{100}$

The amounts of silt in the Vistula and Rhone appear extremely large: the amounts in the Vistula are said to have been recorded when the river was partly frozen. Experiments made on the Indus† gave the proportion of silt to water by weight in the flood season (end of July and early in August) as about an average of $\frac{1}{237}$, the velocity of the water being from $3\frac{1}{2}$ to 5 feet a second: an analysis of the silt showed

* 'Report on the Physics and Hydraulics of the Mississippi River,' 1876, pages 134 *et seq.*

† 'Roorkee Professional Papers,' 1st series, vol. ii., "Indus Silt Experiments," by Colonel Tremenheere, R.E., page 24.

that it contained about equal parts of sand and of rich fertilising mud. The Nile silt contains about the same proportion of fine sand, and Dr. Letheby * calculated that the proportion of silt to water in the flood of the Nile in August was $\frac{1}{666}$ by weight. Experiments were made on the Ganges by Mr. Medlicott,† near the head of the Ganges Canal, where the velocity is great (probably 10 to 12 feet a second), with the result that the maximum amount of silt found was $\frac{1}{123}$ by weight, and this appears to have been an extreme example and a somewhat doubtful one, an average of four examples in August and September giving only $\frac{1}{760}$. The Ganges at this point is fed mainly by the melting of the snows in the Himalayas, and the water is consequently comparatively free from silt; but in its lower reaches, after receiving the drainage of a large tract of country, the water is heavily charged with materials in suspenpension. Mr. Medlicott's experiments show that the water in the Ganges Canal at Roorkee, some eighteen miles from the point where the canal draws its supply from the river, is, at times of full supply, sometimes far more heavily charged with silt than the water in the river, the proportion of silt being as high as $\frac{1}{43}$. This circumstance is interesting as confirming the fact that water which is not fully charged with silt, will pick up silt from the bed of a canal, even although its velocity in the canal is far less than it was in the river from which it was drawn.

The investigations made into the quantity of silt in river water have led to some interesting calculations as to the quantity of solid matter which is carried to the sea by various rivers. Col. Tremenheere estimated that the Indus, during the 100 days of flood, carried about 119 millions of cubic yards of silt to the sea; and Mr. (now Sir) Benjamin Baker calculated that the Nile deposited 49½ million tons, or say 40 million cubic yards in the Mediterranean during the year. These quantities would be sufficient to cover 38 square miles and 13 square miles respectively to a depth of one yard. The ordinary flood discharge of the Indus at Sukkur is about 400,000 cubic feet a second,‡ and that of the Nile about 300,000 cubic feet a second.§ An instance of the rapidity with which the waters of the Nile will deposit silt, when the conditions induce a rapid settlement of the mud held in suspension, is given by Mr. Willcocks. He says:‖—"I measured the rate of silt deposit

* 'Proceedings of the Institution of Civil Engineers,' vol. lx. page 376.

† 'Asiatic Society's Journal,' vol. xx. parts 3 and 4.

‡ 'Roorkee Professional Papers,' 1st series, vol. ii. page 27.

§ 'Proceedings of the Institution of Civil Engineers,' vol. lx., "The Nile," by B. Baker.

‖ 'Report on Reservoirs in Egypt,' by Mr. W. Willcocks, April 1891.

under No. 2 arch of the Damietta Barrage, where there was slack water. The amount deposited was as follows:—

			Metres.
14th	August,	1886	0·48
15th	„	„	0·15
16th	„	„	1·31
17th	„	„	1·10
18th	„	„	0·10
19th	„	„	0·50
		Total	3·64 metres (12 feet)

of silt in six days of August. Between the 9th and 26th of August, or in eighteen days, 6·50 metres (21⅓ feet) of silt were deposited under that arch. The silt had then reached the height of the flood surface, and could rise no more."

One of the most important points to be considered before an irrigation work of any kind is undertaken, is the amount and quality of the silt in the source from which the water is to be obtained. In the case of canals taking off rivers of high velocity, and which probably carry but little fertilising matter, but a good deal—at certain times—of sand or even of shingle, the problem is to design the head-works so as to exclude to the utmost the coarser materials lest they materially diminish the discharge of the canals. In the case of rivers with a more moderate velocity, the problem is how to arrange matters so that the heavier particles, which float in the lower strata of the river and which are sometimes swept along the bed of it more than actually held in suspension in its waters, may be excluded, and the lighter fertilising atoms may not only be taken into the canal but may be carried along it and its branches and finally deposited on the fields. Again, in rivers with still lower velocities, such as the Indus and the Nile, the problem is rather how to design the canals so as to carry to the fields all the silt which can be obtained.

Taking, first, rivers of high velocity, an instance of the partial blocking of a canal by shingle and boulders is seen at the head of the Ganges Canal at Myapore,* where the canal is drawn off a branch of the main river, which has a slope of about 10 feet a mile above the canal head. The Myapore dam was constructed across this branch, and the head-sluice of the canal was placed in the canal itself, about 350 feet back from the line of the dam. The dam was originally constructed with a series of

* See sketch, page 131.

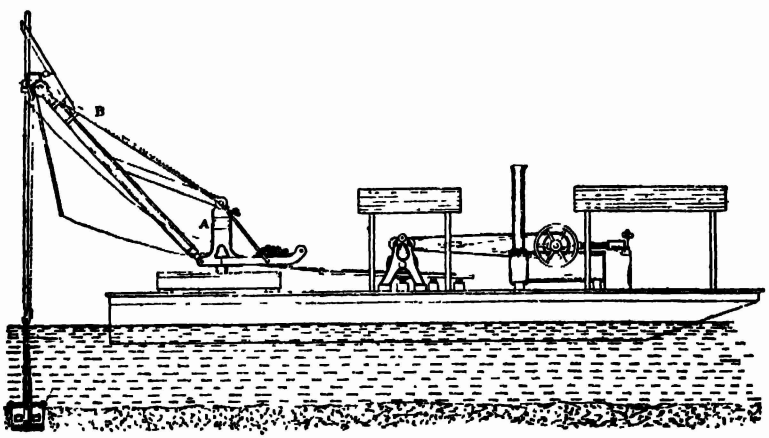
small piers along the crest of it with openings of 10 feet between them. It was found that the shingle travelling down the bed of the river was obstructed by the dam and was deposited largely in the channel just above the head-sluice. The deposit of the shingle has been checked by the construction of seven powerful under-sluices in the dam each 20 feet wide and with a floor-level 12 inches below the old one, and it is intended to build a new head-sluice across the head of the canal and on a line diagonal to the stream so that the shingle may be carried past it, and not deposited, as it now is, in the comparatively quiet water of the channel between the weir and the head-sluice of the canal. The new sluice will be so built that the water taken into the canal, may, as far as possible, be drawn from the surface and not from below. This, in a case of this kind particularly, is a matter of great importance, for the shingle travels along the bed. The head of the Eastern Jumna Canal (Plate XXXIV. page 130) is also on a branch from the main river, the Jumna. This branch has a fall of from 13 to 16 feet a mile and it is remarkable how little shingle is carried into the canal, although the fact that shingle does travel down the branch which supplies the canal is proved by the fact that the floors of the two weirs at Fyzabad and Nowshera, which act as escapes to the channel above the canal head, are damaged by the blows they receive from the falling boulders. The draw of these escapes, one of which is immediately above the canal head at Nowshera, appears to be sufficient to clear away the shingle.

The Sone canals in Bengal afford an instance of the great expense which may be caused by silt. The Sone river, above the heads of the canals which take off on either bank above the weir, has a fall of about 2 feet a mile (0·37 per 1000) and a maximum velocity of about 7·5 feet a second. It carries a considerable amount of silt during floods, a good deal of which is coarse sand, but there is also much fine fertilising matter. The heads of the canals silt up during the months of August and September to an alarming extent, as much as 3, 4, and even 5 feet of sand is deposited in the first quarter mile of the canals, which gradually diminishes in depth until it dwindles away to a few inches at about 5 or 6 miles from the head-sluices: as it decreases in depth the sand diminishes and the deposit becomes less sandy and more muddy. The chief crop irrigated by these canals is rice, which requires the greatest amount of water shortly after the time when the silt deposit in the canals is greatest. It is necessary, therefore, to clear out the silt as it is deposited. Three English-built dredgers and some sixteen or eighteen Indian-built

ones * are constantly employed for two or three months at this work in the flood season, and clearances are effected by hand when the canals are closed for a few weeks in the slack season.

The cost of silt clearance on the first five miles of these canals averages about Rs. 75,000 a year, which is about 15 per cent. of the entire cost of the repairs of the whole system, consisting of some 1600 miles of canals and distributaries. The slope of the main canals is 6 inches a mile (0·094 per thousand), and the velocity in them varies from 2·0 to 2·5 feet per second in full supply; but as the full discharge is not uniformly required the actual velocity at the time of the maximum deposit is often less than 2·0 feet a second. The head-sluice shutters are divided into two parts, and the supply is always drawn from the upper shutters when a sufficient discharge can be obtained in that way; it is the rule, too, to close the head-sluice altogether when heavy freshes, rising above a certain level, but lasting only a day or two, come down the river. The probable extent of the silt deposit in these canals was unforeseen when they were designed, yet it is believed to be greater than that on any other perennial canal in India. The primary cause of this excessive silting lies in the nature and amount of the silt carried by the water, but it would have been better, so far as irrigation interests are concerned, if the slope of the canals and the velocity of the water had been greater, so that a larger proportion of the fertilising mud, which is now deposited, would have been carried forward to the fields. The soil

* These are small steam dredgers which were introduced by Mr. Fouracres about 1876. They are made to utilise portable engines and other plant which existed. They are found more efficient than the larger English ones.

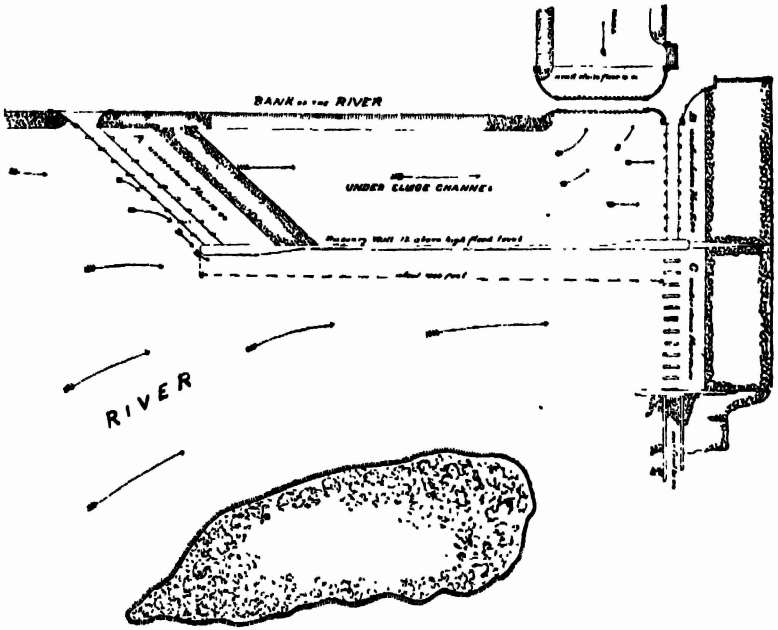


FOURACRES' VERTICAL-ACTION STEAM DREDGER.

would stand a higher velocity than now exists, but the canals are navigable, and a velocity of 2 ft. a second even is a considerable impediment to native boats. The river bed consists of sharp and fairly coarse sand, which is not only carried in suspension, even in the surface water of the river, but is rolled along the bed in considerable volumes in floods: so much is this the case that the general level of the river bed, above the weir, was raised in the course of ten or twelve years practically to the level of the weir crest, which is 10 feet above the original bed of the river, the flow of the sand along the bed having been checked by the weir. The large deposit in the first half mile of the canal is mainly due to the actual sweeping of the sand into the canals along the bed. The floor of the head-sluices is at the same level as that of the under-sluices (Plate XLII., page 142), and the two are close together, so that, when the lower vents of the head-sluices are open, the rolling sand has an easy passage into the canal: it is not always possible to keep the lower vents closed, and it is probable that, even when they are, a certain portion of the rolling sand is drawn over in the whirl near the sluices. The fact of the silting up or raising of the river bed above the weir shows that it is absolutely necessary to have powerful under-sluices acting in front of the head-sluices of the canal, or there would be no channel to them in the dry season; but, at the same time, there is no doubt that the great velocity which is thus induced immediately in front of the head-sluices, not only increases the silt in suspension to some extent, but also increases the roll of sand on the bed. It has been suggested that in cases such as this one a remedy for the evil might be obtained by constructing the head-works as shown in the sketch on the next page.

The under-sluices B and C together would have a capacity rather greater than that considered necessary to keep a good channel open to the head-sluice, but the under-sluice B would have its floor 5 feet lower than the floor of C and the floor of the head-sluice. The under-sluice B would be fitted with draw-gates in tiers, so that the discharge, even in floods, could be regulated through it. Between B and C there would be a wall carried above high flood level, running up-stream, parallel with the main current, which would divide the under-sluice channel A B from the main body of the river. At the upper end of this wall the under-sluice A would be built with its floor at the same level as that of under-sluice C (or slightly above it, according to the slope of the bed of the river). This sluice A would have draw-shutters, but they would only close a portion, say 4 feet, of the lower portion of the vent. The action of this arrangement would be this: under-sluices C would be open during

all the flood season, and the "draw" from them would keep a channel open through the deposits above the weir. The shutters of under-sluice A would usually be kept down, so that the moving sand on the bed would be checked at that point, and diverted towards C: at this point, A, the velocity in the stream would be less than it is immediately in



SKETCH OF HEAD-WORKS IN A RIVER CARRYING HEAVY SILT.

front of the under-sluices where the head-sluice is usually placed, and the rolling sand could be more easily checked. The water at A would be drawn from the surface above the row of shutters. In the under-sluice channel A B, the velocity would be regulated by the manipulation of the shutters in B, so that it was only moderately in excess of that in the canal. The result would be that a considerable proportion of the heavier sand would be deposited in the under-sluice channel between A and B, which, under present circumstances, is deposited in the canal. In time the under-sluice channel A B would become silted sufficiently to impede the discharge of the canal. Then the shutters of both A and B would be completely raised, and a strong stream would be sent through the under-sluice channel, which would scour out the deposit or a good deal of it: at this time the canal would, if possible, be closed. The velocity in the under-sluice channel would be considerably augmented by the drop in the floor-level of the under-sluice B, and the height of the head-sluice

floor above the bed of the under-sluice-channel opposite it would impede the progress of sand into the canal. It might be that it would not always be possible to scour out all the sand deposited in the under-sluice channel A B, especially if it were of a coarse nature: in that case it might be necessary to dredge some portion of it out: the dredged material could be easily discharged into the river, and the heavy expense which is now incurred in discharging it by a long lead from the canal would be avoided. The plan would be an expensive one in first cost.

The Sone river, which supplies the Sone canals, has about the same surface-slope and velocity as the Sutlej river, which supplies the Sirhind Canal in the Punjab. The beds of both rivers are sandy, but the sand in the Sutlej is finer than the Sone sand. The Sone Canals silt badly. The Sirhind Canal in its upper reaches hardly silts at all; and the comparatively small amount of silt which does accumulate is removed, without dredging, by a system based on the same principles as those which underlie the proposed method of dealing with cases similar to that of the Sone. The main line of the Sirhind Canal and one of the two main lines of the Sone canals compare thus:—

	Sirhind.	Sone.
Width of base	200 feet	180 feet.
Slope of bed	0·125 per 1000	0·094 per 1000.
Velocity in full supply ..	2·98 feet a second ..	2·44 feet a second.

But the actual velocity in the Sirhind Canal rarely exceeds 2·5 feet a second. The banks at the head of the canal are very sandy and have been considerably damaged by the flow of the water, so much so that in parts it has been necessary to reduce the side slopes from 1½ to 3 to 1. The Sirhind Canal for the first 20 miles or so runs fairly parallel to the river at about 3 miles from it; in the 12th mile a regulator is built across the canal, and there is a powerful escape above the regulator, with a fall of 5 feet, which is connected with the river by an escape channel. When the canal was first opened, the silting at the head, above the regulator and escape, seemed likely to be serious, and, as the full discharge of the canal was not then required, the supply was reduced as low as possible, with the idea that the deposit would be reduced. It was found, however, that the result was an increase in the silt. So the discharge of the canal was again increased, and the surplus was discharged back into the river through the escape in the 12th mile; this had the

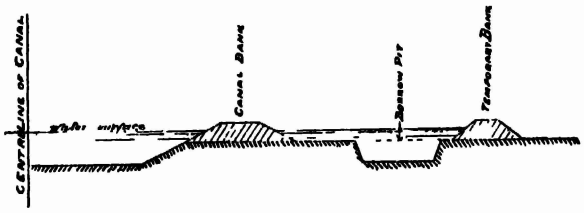
effect of checking the deposit of silt during the flood season. And not only so, but it was found that, if the same thing was done during the other seasons of the year, when the water in the river was comparatively clear, indeed almost quite clear, the silt which had been deposited during the flood season was scoured out by the water, although the velocity at that time in the canal was actually less than it had been during the flood season, when the silt was deposited. This is another instance (page 37) of water not fully charged with silt taking it up from the bed of a canal. It is rather remarkable that silt should be lifted by water flowing at a less velocity than the water which had deposited it, but the fact seems indisputable. The method which has been successful in keeping the head of the Sirhind Canal clear is substantially the same as that which has been suggested above for rivers carrying heavier silt, but it cannot be applied in all cases, as it may not be always possible to construct an escape back to the river.

The main difference between the cases of the Sone and the Sirhind canals lies in the nature of the silt; it is much finer in the latter case, and consequently is carried much farther by moderate velocities: although the first 12 miles of the Sirhind Canal are kept fairly clear, and there is, consequently, no necessity to employ even a single dredger to ensure the full supply to the canal, the silt does accumulate in the lower reaches and in the heads of the distributaries. It is noticeable, however, that these deposits are mainly in the form of silt berms on the banks, and that in the larger canals these silt berms most frequently occur at points where there have been sand spurs thrown into the canal by rain washings, showing that the velocity is usually sufficient to carry the silt forward, and that it is only deposited when the flow of the water is checked by obstructions on the banks.

On the Lower Ganges Canal, and in the Agra Canal also, there are escapes back into the river, a mile and a half or two miles below the weir, which are sufficiently powerful to scour out the greater part of the silt which is deposited in the flood season. In these cases the silt is of an extremely fine nature, and a great deal is carried forward in the canals: no dredgers are employed. The scouring sluices are perhaps rather too close to the heads of the canals. In these cases the maximum velocity of the water is under 2·5 feet a second.

Both at the Sirhind Canal and on the Lower Ganges Canal a system has been tried for silting up the borrow pits which have been cut to form the banks at the lower ends of the reaches where the canal is in embankment, and the water surface above the level of the ground.

The borrow pits have been cut parallel to the canal bank in varying lengths as might be convenient: each pit has been enclosed with the help of a second bank, thrown round three sides of it, and connected with the canal embankment. At the upper and lower end of each enclosed space a cut has been made, connecting it with the canal, so that the water can flow in at the upper end and out at the lower, the space enclosed being formed into a reservoir. These cuts are smaller



SIDE BORROW PITS.

than the pits, so that the velocity is checked. It was anticipated that the pits would be nearly filled in a few years and that the second bank could then be levelled off into the remains of the pit, and the land sold again. The plan has only succeeded to a small extent, the upper openings silt up and the flow into the basin is reduced, so that, as the borrow pit silts up, the rapidity of its silting becomes more and more reduced, unless the channel into it is frequently reopened.

It is always a difficult question to decide whether it is better, if possible, to keep up a high velocity throughout the system, and to pass silt forward on to the fields, or to try and keep it out of the smaller channels by permitting its deposit in the larger ones by maintaining a low velocity. In the Bari Doab Canal in the Punjab, which draws its supply from a river of great velocity in the boulder formation, and where the velocity of the canal is also very high—from 3 to 6 feet a second—the silt, which in this case is very sandy, is carried down the main channels by the high velocity, and deposited in the heads of the minor channels, where, in course of years, huge silt banks, covering a considerable width of land, have accumulated. This silt is not suitable to place on the land, as it is too sandy, and it will soon become a difficulty to know how to dispose of the accumulations. In other canals, such for instance as the Orissa canals taking off the Mahanuddee river on the east coast, the silt is almost entirely advantageous to the land, and it is desirable to distribute it as widely as possible over the fields. The cultivators in Orissa, during the rainy season, when the rice crop is

under irrigation, will often endeavour to drain the water off their fields and irrigate them again from the canals whenever a freshet in the river brings an extra quantity of silt into the water.

The Rayah Behera is one of the three main canals which take off above the barrage or weir on the Nile about 15 miles below Cairo. The canal had been practically useless since its construction, as it silted up so badly that no water could be passed down it during low Nile. The difficulty was considered insurmountable, and two pumping stations were erected about 12 years ago, one on the Rayah Behera and another on the Mahmoudiah Canal, which is in connection with it, to supply water for irrigation, during the period of low Nile, by pumping direct from the Rosetta branch of the river. The pumps at the station on the Rayah Behera were capable of delivering 1000 cubic feet of water a second. The amount spent annually by the Egyptian Government in pumping at these two stations was about 60,000*l.* The canal as constructed had a bed width of 65 feet and a slope of 0·075 per thousand. The water-level in the flood season was designed to be about 20 feet above bed, and in the season of low Nile there was to have been 9 or 10 feet of water in the canal. The canal had been practically useless for years, as it silted so badly; it had been closed entirely during high Nile. In 1885 and 1886 the experiment was made of running the canal during the Nile flood, in the hope that a scour would be induced and the bed deepened. The result was exactly the opposite, and the canal became completely choked. But the silt deposited in the canal was not entirely due to the deposits from the Nile water: the canal runs for a part of its length through a broad sandy plain which is said to have been once cultivated land but which is now desert, in this part the velocity of the water was greater than the friable banks could stand, and they were cut away. The sandy soil, however, when it had been moved from the banks, was only carried forward a comparatively short distance by the stream, and was then deposited in the bed of the canal, the deep bed silted up as the banks cut away, with the result that the section was altered completely; so that, instead of the canal being a neat cutting of 65 feet base and 20 feet deep, it degenerated into a flat sandy trench 150 to 200 feet broad and 8 or 10 feet deep. This alteration of the section checked the flow of the canal in its upper reaches, with the result that the waters of the Nile flood deposited large quantities of silt and the canal was completely choked, the bed being above the summer level of the river at the head of the canal. A still further difficulty was caused in the Rayah Behera by the drifting

sand of the desert which was continually being blown into the canal and tended still further to choke it.

This latter difficulty was dealt with in two ways: first by the erection of sand screens made of lines of posts and mats, which checked for a time the onward movement of the sand by the wind, and, secondly, by flooding the desert during high Nile with muddy water and planting grass on it. It so happens that there are a series of "basins" lying above the desert in question from which it is possible to flood it—or the greater portion of it—to a depth of from 3 to 6 feet. The mud which is deposited by this water cakes on the surface of the sand when the water is drawn off and the slight crust is sufficient to hold the sand against the force of the wind. It seems probable that in time this desert will again be made culturable by this process. It has been calculated that the measures which have been adopted have stopped something like $3\frac{1}{2}$ million cubic feet of sand from being blown into the canal every year.

But the more serious difficulty was the alteration in section due to the combined scour and deposit which not only occurred when the canal was opened during the high Nile in 1885 and 1886, but during the summer months also, so that even with extensive silt clearance and dredging only a dribble of water could be passed down. A series of groynes have been constructed at the places where the banks used to cut; they are placed at varying distances apart according to the circumstances, but generally about 650 feet where the canal is straight, 325 feet on the inside of curves, and 200 feet on the outside or concave side of curves where the cutting is always greatest. These groynes were in the first instance made of unburnt brick faced at the ends with burnt brick, but these did not stand: afterwards timber and sandbag groynes were tried; these would probably have answered, but the timber and sandbags were stolen in large quantities by the Bedouins. Groynes of burnt brick were then made, and these have stood well. In addition to the groynes the greatest care was taken to plant long grass and a kind of willow bush at frequent intervals (a foot or so apart) at all places where the bank was friable. This grass acts most effectually in retaining the slopes; it grows well in sand, and flourishes as soon as a little silt is deposited at its roots. The groynes are carried about 12 inches above high water level; they are simply banks of packed bricks, the crest being 3 to 4 feet wide, and the side slopes 1 to 1. (Plate XIII.)

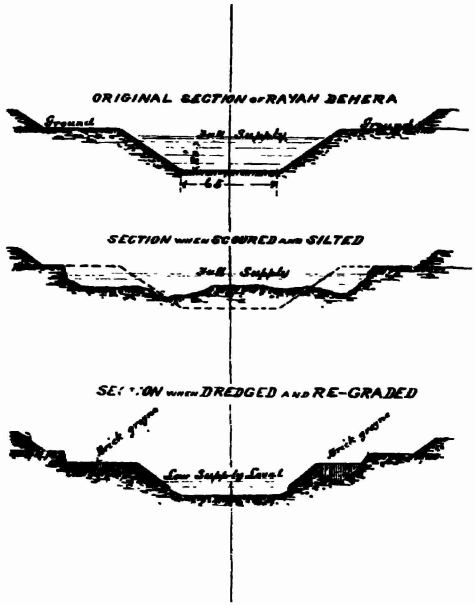
The improvements of the canal were taken in hand by Mr. Foster in 1886: about 28,000*l.* has been spent since then on the construction of these groynes, and during the last three years some $4\frac{1}{2}$ million cubic

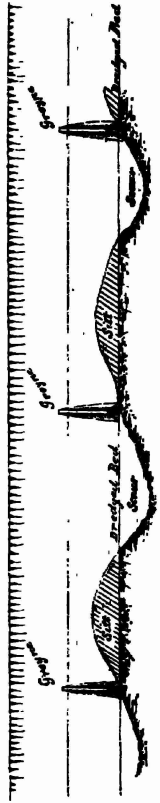
yards of silt and washings from the banks have been removed, at a cost of 140,000*l.*, the total expenditure up to the end of 1892 being 216,285*l.* The slope of the bed has been reduced to 0·05 per 1000.* The result has been eminently satisfactory. The washing of the banks has been stopped and the current controlled; the silt which is being gradually deposited behind the groynes is bringing the parts which were cut away back to true section, and the dredgings from the canal are being used for the same purpose. The discharge in the season of low Nile has now been assured, and it considerably exceeds that which used to be given by the pumps, which are now stopped at both the pumping stations. It has been calculated that, independently of the value of the increased supply, the improvements have effected a cash saving of 34,500*l.* a year.

The same action which for a time destroyed the efficiency of the Rayah Behera has taken place in the perennial Ibrahimiyah Canal in Middle Egypt, but not to so extreme an extent: the banks cut away and the bed filled up, so that in some places the current divided into two parts flowing under either bank, and the supply in the time of low Nile was greatly reduced. This canal is in stiffer soil than that portion of the Rayah Behera which has just been described, but the depth and velocity are greater. The canal had a bed width of about 200 feet, and a surface slope in the flood season of $\frac{1}{1300}$ (= 0·08 per 1000) with a velocity about 4 feet a second. Rubble stone spurs have been employed by Major Hanbury Brown, R.E., in this case with excellent results. The spurs (Plate XIII.) have been constructed in pairs, immediately opposite each other, with a crest slope of 1 in 5 and side slopes of 1 to 1. They are placed generally about 800 feet apart (four in each kilometre). The bed width has been reduced to 131 feet (40 metres) and it is dredged annually to fixed bed levels which give a slope of $\frac{1}{12000}$ (=0·02 per thousand). The 1 to 1 slope at the point of each groyne terminates at the edge of the new bed. A continuous line of these groynes has been constructed for a length of more than fifteen miles of the canal, at a cost of about 18,000*l.* The result has been to check completely the cutting of the banks, and to cause the side slopes between the groynes to silt up to a certain extent, as is shown by the contour lines in the plan on Plate XIII., the bed of the canal scours below each groyne and silts above it to varying depths and heights, while the silting on the side slopes, which are protected by the groynes, is greatest above and least below each groyne. In some cases the eddy below a groyne and the scour of

* 'Administration Report of Egyptian Irrigation,' 1890, pages 56 and 86; and 1891, pages 159 to 167.

GROYNES IN RAYAH BEHERA





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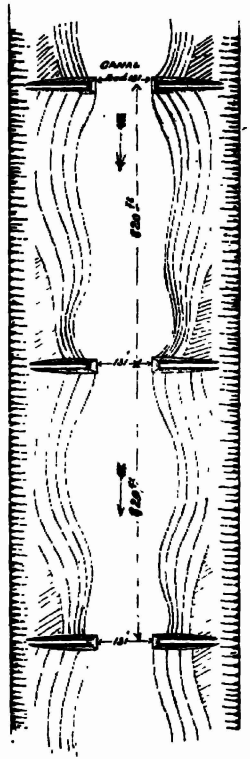
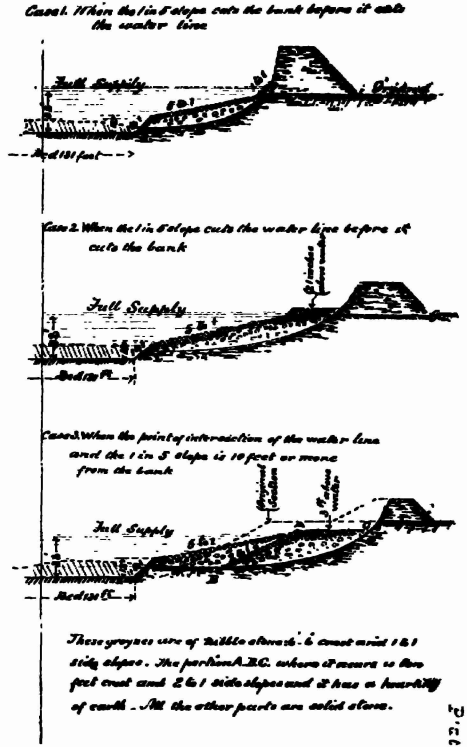


PLAN of CANAL

GROYNES IN IBRAHIMIAH CANAL



These groynes are of rubble stone 6 crest wide 1 & 1 side slopes. The portion A.B.C. where it occurs is five feet crest and 2 & 1 side slopes and it has a backing of earth. All the other parts are solid stone.

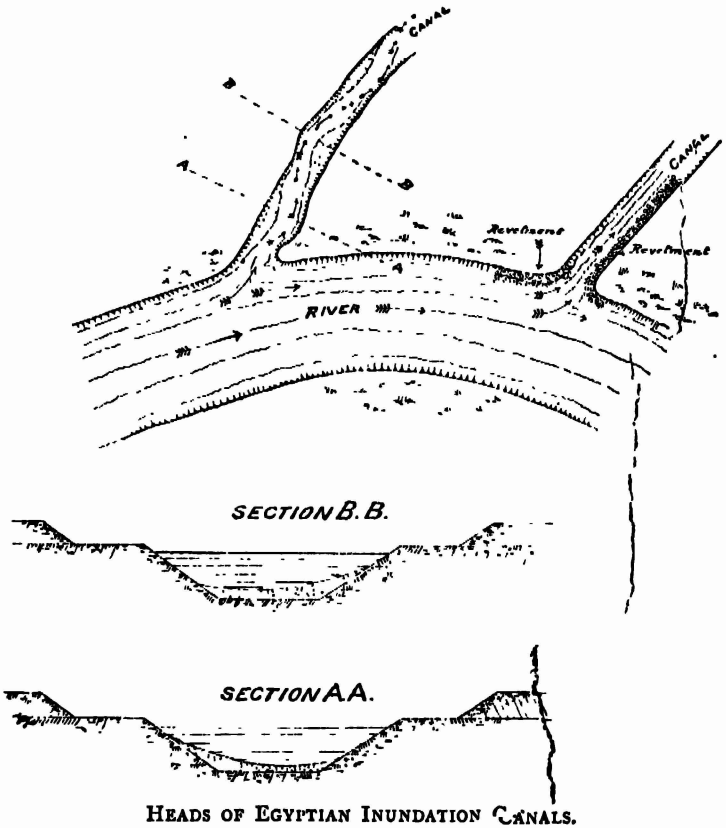
PLATE XIII

the bed has been sufficient to undermine the spur, and it has had to be reconstructed. The silting on the side slopes is tending to gradually restore the true section of the canal, and the action on the bed has enabled a larger summer supply to be passed with less dredging. The Inspector-General of Irrigation in Egypt is, however, of opinion * that the groynes are not quite close enough together to effectually cure the silting which affects the summer supply. The groynes have been extended year by year, and it has been noticed that the effect at the end of the line of groynes has been that a bank of silt was thrown up 1300 feet below the last pair of groynes, and it has been argued that, as the effect of the last pair extends to that distance, the effect of a continuous line of groynes must be continuous. The result has been that the amount of dredging necessary has been already reduced, and it is expected that when the work is entirely complete, the economy in this respect will be very large. Grass and willows have been planted in many parts on the newly deposited silt at the edge of the low level of the water, to protect the bank and to encourage the deposit.

Large quantities of silt are excavated every year from the inundation canals of Sind and the Punjab: the silt accumulations sometimes become so great that it is cheaper to cut a new head altogether than to continue to lift the silt over the accumulation of former years. In Egypt also the annual clearances from inundation canals are enormous. Both in India and Egypt it would usually be advantageous to carry all the silt forward, and it is remarkable that, although the great majority of inundation canals silt more or less, the amount of silt varies greatly in different canals, and in some there is actually hardly any at all. So that it might be thought that it would be possible to construct inundation canals which would not silt. It is certain, however, that this is not possible under some conditions—as, for instance, when a canal has to be taken off a cutting bank—but there is no doubt that much of the silting which now occurs might be avoided. One of the most essential points—to which very little attention is often given—is the proper grading and sectioning of canals: many old inundation canals are too large at their offtake from the river, and the reaches below are unable to carry the quantities which the upper reaches are capable of discharging. The result is that the velocities are checked in the higher reaches and silt is deposited. It seems to be a fact which cannot be easily explained, that, under some circumstances, the deposit of silt is not so much caused by the actual diminution of velocity in the water, when

* 'Administration Report of Egyptian Irrigation, 1890,' page 60.

it is drawn from a river into a canal, as by variations in the velocity after the water has entered the canal. There is no doubt that silt encourages silt, and that a canal which is regularly aligned, truly graded, clean in section, which has well laid out curves of large radius, and in which the discharge introduced at the head is regularly disposed of, either on to the fields or by escapes, without alteration of velocity, will silt less than one of higher general velocity which is badly aligned and graded, and in which there is frequent interference by regulators. A very substantial decrease has been effected in the silt clearance of some Egyptian canals



HEADS OF EGYPTIAN INUNDATION CANALS.

by attention to this principle. It has been already noticed that one of the most certain means of making the head of an inundation canal silt is to regulate the discharge by a masonry work situated some distance from the head. Experience in Egypt has shown that one cause of silting is the oscillation which is set up in a canal by the form of entrance from the river. When a canal is taken off at an abrupt angle, the lower

bank cuts away below the head and the current* is deflected as shown in the sketch ; the oscillation of the current, which often extends a long way, causes a deposit of silt in the bights, and the erosion, perhaps, of the bank at the bends : the cross sections show the result. It has been found that if the down-stream bank of the canal for some distance below the head, and the up-stream bank immediately at the head are revetted with stone, so that the cutting of the bank is stopped and the oscillation checked, the amount of silt is reduced, although the velocity is unaltered. The flow of the stream is directed along the line of the axis of the canal instead of oscillating from side to side of it.

* 'Administration Report of Egyptian Irrigation, 1889,' by Col. Justin Ross, C.M.G., page 42.

CHAPTER IV.

FLOW-OFF FROM CATCHMENT AREAS, EVAPORATION, ABSORPTION.

Necessity for Reservoirs—Reservoirs liable to fail when most required—Maximum Discharge from a Catchment—Coefficients in Dickens' and Ryves' Formulæ—Maximum Discharge from small Catchments—Average Flow-off a Catchment—Flow-off dependent on condition of Catchment—Loss by Evaporation and Absorption in Reservoirs—Absorption checked by Silt—Instances of Loss of Water in Canals by Evaporation and Absorption.

WORKS for the storage of water for purposes of irrigation are necessary in India wherever the minimum discharge of the rivers or streams of the neighbourhood, during the irrigating season, is insufficient for the crops. In many parts, as in Baluchistan and Rajputana, the streams may be torrents for a few days, and almost dry—or even quite dry—for the rest of the year. In the higher lands, where the rivers have comparatively small catchments and the slope of the ground is rapid, the rainfall, except in heavily wooded districts, passes off rapidly, and little is available for irrigation in the dry weather, unless reservoirs are formed in gorges in the hills.

One of the most important matters in connection with any tank or reservoir project is to ascertain the amount of water which may be expected to flow into it. Not a few reservoirs have been constructed which have never filled to more than a fraction of their capacity, and, not unfrequently, the error has been caused by accepting the rainfall data of one or two stations as a true gauge of the fall over the entire catchment area of the reservoir. Too much care can hardly be taken to get as many observations as possible in different sites in the catchment. It has also to be borne in mind that the supply in a reservoir is most required during a year of abnormally deficient rainfall, and, in such a year, the supply to the reservoir is least. Years of abnormally deficient rainfall occur at long intervals, and may not be displayed in the returns available of any particular locality; so it is well in preparing a project

to allow a liberal discount in the available data on this account. It does not, of course, follow that a tank or reservoir will be useless because it might prove to be so in an abnormal year—the results obtained in ordinary years may justify its construction; but instances are not wanting in which a reservoir was hardly necessary in ordinary years and failed to be of any service when scanty rainfall produced a demand which could not be supplied.

But even if the rainfall returns of any particular catchment are complete, there is often no little difficulty in deciding, first, the maximum discharge from the catchment in periods of maximum rainfall; and, secondly, the amount of "flow-off" or the proportion of the total rainfall which will be discharged off the catchment. It is necessary to estimate the first quantity in order to design the bye-wash or escape from the reservoir, and the second is essential, in order that an estimate may be framed of the amount of water which will be stored.

The maximum discharge from any given catchment is a factor which enters into many problems in connection with irrigation works and embankments. It depends primarily (1) on the maximum rainfall; (2) on the nature of the soil; (3) on the surface slope of the soil of the

Province.	Name of River.	Approximate Length of Channel of River in miles.	Approximate Average Annual Rainfall in the Catchment in inches.	Area of Catchment in square miles.	Maximum Discharge in cubic feet per second.	Discharge in cubic feet per second per square mile of Catchment.	Depth of "Flow-off" from the Catchment in inches over the entire Catchment in 24 hours.	Coefficients in Dickens' Formula, $D = C\sqrt[4]{M^3}$.
Madras*	Cauveri ..	472	30 to 40	27,700	320,000	11	0·4	149
	Vellar ..	?	30 to 40	1,600	85,000	53	1·9	336
	Manjera ..	?	?	6,500	410,000	63	2·3	567
Bengal ..	Sone	325	40 to 50	23,000	830,000	36	1·3	444
Orissa ..	Mahanuddee	520	50 to 70	45,000	1,570,000	35	1·3	508
N.W. Provinces	Betwa ..	360	30 to 40	9,000	750,000	83	3·0	811
Do. ..	Kali Nadi	150	30 to 40	2,377	130,000	55	2·0	382

* Taken from 'Madras Irrigation Manual,' 1890.

catchment; (4) on the area and configuration of the catchment; and (5) on the situation of it with reference to the monsoon current. No formula has yet been proposed which deals adequately with the problem. The two most commonly used are Dickens' formula $D = C\sqrt[4]{M^3}$, and Ryves' $D = C\sqrt[3]{M^2}$ (where D = discharge in cubic feet per second, M = the area of catchment in square miles, and C is a coefficient). These depend for their usefulness entirely on the value given to the coefficient C, which varies, as a matter of fact, from 150 to 1000, and even to more than 1000 in very abnormal cases. The table on preceding page shows the maximum discharges in certain rivers having catchment areas of less than 50,000 square miles.

A comparison of some of these is interesting as displaying the difficulties of assessing the proper coefficient to apply to Dickens' formula. In the case of the Sone and Mahanuddee, for instance, the larger coefficient in the latter case is probably mainly due to the greater rainfall; but in the cases of the Vellar and the Betwa, where the rainfall is about the same, the cause of the enormous discharge in the latter case is the nature of the catchment area itself. The catchment of the Vellar is believed to be generally thickly wooded, but the Chief Engineer of the North-west Provinces* speaks of the Betwa as "leaping down from the high lands of Central India to the level of the valley of the Jumna in channels . . . worn in the vast table of granite and trap rock which covers the country;" and he assumed that 80 per cent. of the rainfall over the entire catchment might be drained off it by the river. The large discharge obtained from the Manjera, which is a tributary of the Godaveri, is held to be due to the "basin being long and narrow, with the length lying generally in the direction of the monsoon current:" it is a good example of the effect which may be produced by the configuration and situation of a comparatively small basin. The Kali Nadi is a remarkable case of a flow-off which is considered to have been unprecedented in the North-west Provinces. The Nadi drains a narrow basin, and passes under the Lower Ganges Canal through an aqueduct. This aqueduct was originally built on the hypothesis† that the maximum drainage off the catchment would be 9 cubic feet per second per square mile, or 0·33 inches in depth over the entire catchment in twenty-four hours. But the actual discharge of a flood in July 1885 was just six times as great, and the result was the entire destruction of the aqueduct.

* Report by Col. Greathed, Chief Engineer N.W.P., dated 2nd Nov., 1874.

† 'Note on the Failure of the Kali Nadi Aqueduct,' by the Inspector-General of Irrigation, August 1885.

The maximum discharge from large catchments is greatly affected by the reservoir capacity of the river channel itself, and, in such rivers as the Ganges, by the volume held back in the vast areas which are flooded on either side of the river in great floods. The maximum flood discharge of the Ganges at Sahibgunge (above the head of the delta), is given * as 1,500,000 cubic feet a second, which is considerably less than the united discharges of the Ganges, Gogra, Sone, and Gunduk in ordinary floods at their confluence near Patna (Plate XXV., page 94). The Ganges has a total length of about 1500 miles, and a catchment of 390,000 square miles, on which the average annual rainfall is from 40 to 60 inches. The Godaveri river in Madras drains 115,570† square miles of country, subject to an average annual rainfall of 30 to 40 inches, and has a channel 900 miles in length: its maximum discharge is given as 1,000,000 cubic feet. The great difference in these two cases is primarily due to the gentler slope of the valley of the Ganges and the large reservoir capacity of the channel and spills of that river.

These facts give some guide to the maximum discharges to be expected from large areas in India, but no method has been as yet ascertained for fixing the value of the coefficient in the formulæ which are usually employed. All that can be done is to take the nearest parallel case which can be found, of which the data are known, and to estimate the coefficient according to the variation in the circumstances. In Madras, Ryves' formula ($D = C\sqrt{M^2}$) is generally used with the coefficient

C = 450, within 15 miles of the coast.
= 563, for the tract 15 to 100 miles from the coast.
= 675, for limited areas near the hills.

The maximum discharge from small catchment areas, varies, of course, more largely than that from larger ones, according to the effect produced by the five causes which have been already mentioned. Small areas of a few square miles of rocky ground which have previously been saturated by slight showers have been known to pass off the entire discharge of a heavy shower within three hours of its fall; while observations on very flat land cultivated with rice in lower Bengal, show that the maximum discharge will not exceed one-tenth part of the gross fall on the catchment in any period of 24 hours, and that, usually, it is much less.

* 'Project for a Navigable Canal from the Ganges at Sahibgunge,' by Col. G. A. Searle.

† 'Madras Irrigation Manual,' 1890.

In dealing with small catchments, say of 100 square miles and less, it is important to remember that, in the plains of India, falls of more than 10 inches in 24 hours, although they are occasionally registered, are extremely local in their incidence and rarely extend over more than a fractional part of a catchment. On the other hand, there is always a danger of underrating the probable discharge from catchments on which the average annual rainfall is small, on the erroneous supposition that the fall in short periods bears some proportion to the annual fall. On the area commanded by the Chenab Canal in the Punjab, the average annual rainfall is 14 to 15 inches only, but falls of 5 inches in 5 hours, 6 inches in 12 hours, and 8½ inches in 24 hours are recorded in the reports on the canal, and it is stated that at two places (Chenáwán and Shahjamál) the rainfall in a period of six days was 77 and 68 per cent. respectively of the entire average rainfall of the year. When this canal was first opened the drainage crossing it was greatly underestimated and large additions to the original works had to be made to pass the discharges caused by the heavy falls in short periods. These falls were, in fact, larger than are found in some districts where the annual fall is much greater. Thus, an analysis, extending over a period of 13 years, of the rainfall affecting an area of rather more than 100 square miles in a part of Bengal where the average annual rainfall is about 60 to 70 inches, showed that, although a fall of 10·87 inches had been recorded in one day, the greatest fall recorded in any period of ten consecutive days had been 13·29 inches: that ordinary heavy falls of rain were those which reached 6 inches in ten days and extraordinary falls of very rare occurrence were those which attained to 10 inches in ten days in June, July, and August, and 13 inches in September and October. It was shown that, on the average of 13 years, there had been, in each year:—

84·15	days	when the rainfall was	less than 1 inch.
12·47	„	„ „	between 1 and 2 inches.
2·98	„	„ „	„ 2 and 3 „
1·0	day	„ „	had exceeded 3 inches.

These were facts affecting 100 square miles based on the average of several recording stations: the records of one particular station might give much higher results.

The following data, concerning the flow-off from small catchments, are of some interest. In Lower Bengal, where the rainfall may be 60 to 70 inches in the year, experience has shown that in certain tracts near Calcutta, which are flat and cultivated with rice, a maximum discharge

of 6·7 cubic feet per second per square mile (= 0·25 inches in vertical depth over the catchment in twenty-four hours) is sufficient to prevent damage to the crops. Several drainage projects have been carried out on that basis. But the maximum natural flow-off from such areas is about 27 cubic feet per second per square mile. In the Balasore district, close to the coast of the Bay of Bengal, where cyclonic storms occur, a discharge of 112 and 160 cubic feet per second per square mile (4 inches and 6 inches in 24 hours off the catchment), and even more have been allowed for in certain works on the Orissa Coast Canal.*

A well-authenticated example of the discharge from a small catchment during a cyclonic storm is found in the case of the Red Hills Tank which supplies drinking water to Madras. The tank has a drainage area of 23 square miles of cultivated land on a moderate slope. The following figures, which are taken from Colonel O'Connell's † report on the cyclone of May 1877, show the discharges which occurred in this case on an occasion of abnormal rainfall. The rainfall at the Red Hills Tank during the cyclone was

	inches.
On 17th May	1·00
„ 18th „	12·03
„ 19th „	4·88
Total	17·91

The rise in the surface of the water during this cyclone was entirely due to the drainage from the catchment basin of 23 square miles, which includes the area of the reservoir itself. The rise and the corresponding drainage are shown in the following table :—

Date.	Level of Water Surface at 6 A.M.	Corresponding Volume in millions of cubic feet.	Daily Difference of Level of Water Surface in feet.	Additional Volume entering Reservoir.		Drainage in inches over the Catchment of 23 miles (including Reservoir).
				Per day in millions of cubic feet.	Cubic feet per second.	
May 17th	27·30	253·6886	..	..	..	..
„ 18th	30·95	517·0018	3·65	263·3132	3,047	4·92
„ 19th	34·25	838·0862	3·30	321·0844	3,766	6·009
„ 20th	34·79	921·3674	0·74	83·2812	964	1·56

* Note by the Chief Eng. of Bengal, dated Feb. 1879, on the Orissa Coast Canal.

† 'Madras Government Proceedings,' No. 38, I. of Jan. 14th, 1878.

The quantity draining off in the three days amounts to a total of 12·489 inches. Water continued to run slowly off the catchment basin for nearly a week after the rain had ceased to fall, but the quantity thus discharged did not exceed one-third of an inch, so that the total quantity run off fell short of 13 inches. Taking each day separately, the figures in column 7 for the 18th and 19th of May give coefficients of discharge of 377 and 466 respectively for Ryves' formula $D = C\sqrt[3]{M^2}$, and coefficients of 290 and 359 respectively in Dickens' formula $D = C\sqrt[4]{M^3}$. It is more than probable, however, that these coefficients are too small to represent the maximum discharge, which, especially in the case of cyclonic rain, would doubtless considerably exceed the average discharge from which they are obtained. It has to be borne in mind that this example is recorded in May, when the ground on the catchment was comparatively dry; the run off would have been greater in July or August, when the ground would be damp and not competent to absorb so much of the rainfall.

In the district of Midnapore, where the annual rainfall is about 50 inches, drainage sluices were constructed with sufficient waterway to carry off 81 cubic feet per second per square mile (= 3·0 inches in twenty-four hours on the catchment) off small areas, but this discharge is now considered very large, and the Surpai sluice, which has been recently constructed to drain an area of 106 square miles, will discharge only 20 cubic feet per second per square mile (= 0·75 inches in twenty-four hours) off the catchment.

In Behar, where the rainfall is about 40 inches in the year, the most recent works provide for 40 cubic feet per second per square mile (= 1·5 inches) for areas of ten to twenty square miles, and it has been found that 50 cubic feet is a liberal provision.

In the North-West Provinces the data given in the table on the next page, were adopted * for determining the waterway to be provided in passing drainage under canals and distributaries in a tract where the average annual rainfall is about 32 inches.

The experience of the Kali Nadi Aqueduct † has shown that this table does not allow for nearly sufficient discharge from the larger areas. In the case of certain drainages affecting the Chenab and Jhelum Canal project in the Punjab, 35 cubic feet per second per square mile (1·3 inches off the catchment in 24 hours) was the maximum flow-off which was provided for: the rain varying from 8 to 22 inches in the

* 'Report on the Project of the Lower Ganges Canal,' dated November 1870.

† See page 54.

year, but falls of 6 inches in one day—or even in as many hours—having been recorded. In the district of Sarun in Bengal drainage sluices in the embankments are designed to permit of a discharge of 100 cubic feet per second per square mile; but this is believed to be excessive.

Area of Tract drained in square miles.	Discharges to be allowed for.	
	Cubic feet per second per square mile.	Equivalent Depth in 24 hours over the Catchment in inches.
From 1 to 10 ..	80	3·0
„ 10 „ 20 ..	56	2·0
„ 20 „ 50 ..	32	1·2
„ 50 „ 100 ..	26	0·9
„ 100 „ 500 ..	22	0·8
„ 500 „ 1000 ..	18	0·6
„ 1000 „ 2000 ..	16	0·5
„ 2000 „ 3000 ..	12	0·4

The foregoing examples refer to catchments of agricultural land in the plains, in which the general slope of the country concerned might vary from 6 inches to three or four feet in the mile, and where the maximum daily rainfall would rarely exceed four inches, although it would at times, and in restricted areas, reach to 10 or 12 inches.*

The maximum discharge which may be expected from small catchments in rocky and hilly ground are much larger. The waterway allowed on hill streams crossing the East Indian Railway at Rajmehal is sufficient to carry off 350 cubic feet per second per square mile. Sir Proby Cautley allowed 323 cubic feet (12 inches in 24 hours over the catchment) on hill streams in the Sewalics. In the case of a tank at Satara, which has a catchment of less than three square miles of rocky ground, the waste weir has been constructed to carry off a depth of 3 inches off the entire catchment in one hour, or 1936 cubic feet a second per square mile. The waste weir of the tank at Jubbulpore, which supplies the waterworks of that city from a catchment of 5¼ square miles of rocky ground, has been constructed to carry off 5·44 inches in one hour off the catchment, which is equivalent to the enormous (and

* Even 20 inches has been recorded in extremely abnormal cases.

probably excessive) discharge of 3514 cubic feet a second per square mile, although the maximum rainfall recorded in 24 hours was only 12·49 inches. The waste weir of the tank which supplies the water-works of Nagpur in the Central Provinces, which has a catchment area of 6·6 square miles of low basalt hills, has a maximum discharge of 967 cubic feet a second per square mile, which is equivalent to a depth of 1·5 inches over the catchment in one hour. In these cases, where the slope is very rapid, it is necessary to base the calculations of flow-off not on the daily rainfall, but on the hourly rainfall. The following tables give some interesting statistics concerning the flow-off the catch-ment of the Nagpur tank which has just been mentioned :—

NAGPUR WATERWORKS.—TABLE OF EXTRAORDINARY SHOWERS DURING THE MONSOON OF 1872.*

Date.	Rainfall.			Rise of Reser-voir in feet.	Duration of Rise.		Rate of Flow in cubic feet per second per square mile.	Proportion of the entire Rainfall of each Shower which flowed off the Catchment during the Period of Rise.
	Fall in inches.	Duration of Fall.						
		hours.	min.		hours	min.		
18th June ..	2·24	1	20	unimportant			nil	
3rd July ..	3·92	24	..	1·50	24	..	16	0·16
10th „ ..	0·71	..	20	0·32	3	..	61	0·204
12th „ ..	1·26	..	30	1·00	3	..	106	0·392
9th August	0·97	1	30	0·10	2	..	20	0·065
10th „	3·50	1	45	3·15	3	..	457	0·607
24th „	1·00	..	40	0·60	3	..	109	0·510
7th Sept. ..	0·60	1	0	0·60	5	30	65	0·940
16th „ ..	0·50	..	30	0·40	6	..	41	0·760
	2·20	1	20	2·20	2	50	492	0·983
6th October	0·50	..	20	1·34	3	0	439	0·346
	3 55	..	45					

The most striking fact displayed by these tables is the enormous effect produced on the discharge by the condition of the catchment area at the time of the fall. The fall of 2·24 inches falling in eighty

* Taken from Report No. 27 on the Nagpur Waterworks, dated 28th Feb., 1873, by Mr. A. R. Binnie.

TABLE SHOWING THE MONTHLY FLOW-OFF DURING THE RAINS OF 1872.

Month.	Rainfall of each Month.	Total Rise in Reservoir during each Month.	Quantity of Water received in the Reservoir		Proportion of the Rainfall of the Month impounded in the Reservoir	
			From the Rainfall on the Actual Water Surface.	From the Water flowing off the Ground.	From the whole Catchment Area including Water-spread.	From the Water flowing off the Ground only.
	inches.	feet.	millions of cubic feet.	millions of cubic feet.		
June ..	6·77	0·83	2·996	1·888	0·047	0·018
July ..	12·70	5·72	8·100	36·296	0·227	0·194
August ..	11·82	8·55	11·465	89·670	0·558	0·529
September	7·99	4·90	9·551	81·645	0·744	0·724
October ..	4·37	1·55	5·630	20·800	0·394	0·338

minutes in June when the catchment area was perfectly dry and baked by the previous hot weather, only raised the reservoir by the amount due to the actual depth of the fall on the waterspread: there was no discharge from the catchment, and during the whole month of June less than one-fiftieth part of the gross rainfall on the ground flowed into the reservoir: while on the 16th of September, when the catchment was thoroughly saturated by the rain which had fallen on 55 days out of the previous 89, a shower of 2·20 inches falling in 80 minutes produced a discharge into the reservoir of no less than 98 per cent. of the entire fall on the ground draining into it within a period of three hours, and the flow-off of the whole month was equivalent to 72 per cent. of the entire rainfall of the month. In such small tracts as those referred to in these examples, falls of even five inches in an hour may be expected, and it is necessary to make provision for escaping a large proportion of such a fall (probably from one-fourth to two-thirds) according to the slope of the catchment area. The statement on the next page shows the capacity of the waste weirs on tanks and reservoirs in the Bombay Presidency situated on rivers and streams in hilly ground. The statement shows how great are the discharges which may be obtained in tracks where the annual rainfall is slight.

In dealing with projects which require an estimate of the maximum flow-off a catchment, it is always the best plan, where it is possible, to base the estimate on the discharges recorded in the streams which actually drain the area. It is often possible to ascertain approximately

the highest flood levels and to arrive at the surface slope of the stream: this information, with cross sections of the stream, will afford better grounds for an estimate than can be obtained from formulæ applied to the area of the catchment.

Number of Tanks on which Statistics are based.	Average Annual Rainfall.	Area of Catchment.	Slope of the River above the Reservoir.	Maximum Discharge for which the Waste Weir is designed.
	inches.	square miles.	feet per mile.	cubic feet per second per square mile.
6	from 15 to 30	less than 10	30 to 40	from 528 to 967
10	„ 21 „ 30	from 10 to 50	17 „ 41	„ 645 „ 860
7	„ 23 „ 40	„ 50 „ 100	12 „ 29	„ 438 „ 645
7	„ 23 „ 55	„ 100 „ 600	4½ „ 12	„ 212 „ 645

The maximum discharge from a catchment during any short period is important with reference to the bye-wash or waste weir of a reservoir or tank, but it is essential to ascertain the average (or minimum) flow-off during a long period (or during the period when water can be impounded), in order to know what quantity of water will be stored for irrigation. In considering this problem, which is one of great complexity, an analysis of the rainfall for a series of years is desirable in order to ascertain the rainfall which can be expected under the most unfavourable circumstances; for, as a rule (which is subject to exceptions) the financial success of a reservoir project will depend largely on its efficiency under those conditions. The diagram on next page shows such an analysis of the reservoir rainfall at Jubbulpore in the Central Provinces for thirty-five years.

The figures in the body of the diagram show the number of inches which the rainfall of the year was greater or less than the average of thirty-five years. Thus the fall in 1882 was 16·05 inches greater, and that of 1883 was 4·16 inches less than the average. A study of this diagram shows that:—

The maximum rainfall of any one year (1884) was ..	91·27 inches
The minimum „ „ „ (1885) „ ..	24·21 „
Greatest number of consecutive years in which the rainfall was below the average was	9 years
The average fall during these 9 years was	41·60 inches
The average fall of the three driest consecutive years was	36·94 „

Observations recorded both at Nagpur and at Jubbulpore showed that, in ordinary years, the gross flow-off from a rocky catchment of 5 or 6 square miles in area was 40 per cent. of the entire rainfall. In the Bombay Presidency, where there are thirty-seven tanks and reservoirs having catchments varying from 3 to 600 square miles in area, it is

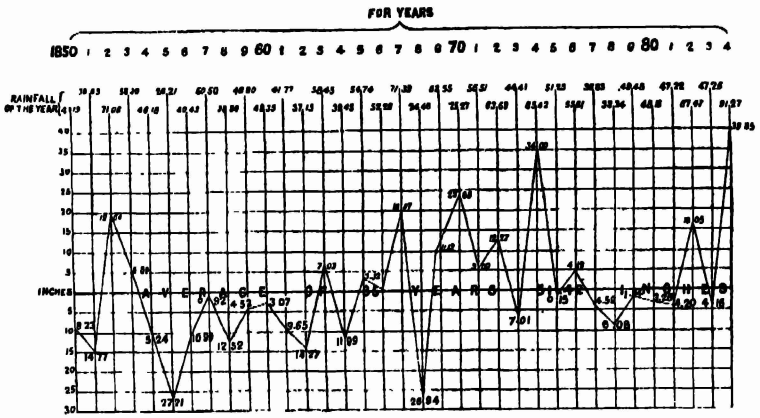


DIAGRAM OF MONSOON RAINFALL AT JUBBULPORE.

generally assumed that 25 per cent. only of the total rainfall (which is generally about 20 to 25 inches in the year) is impounded in the reservoir. But the gross flow-off in years of exceptionally low rainfall bears a smaller proportion to the rainfall than that of ordinary years; so that, if it is considered necessary to base the calculations on the minimum probable supply, as little as 10·0 per cent. of the rainfall of the year has to be taken. The following examples of actual results are interesting.

In the Oopahalli tank at Bangalore in Mysore (an exceptionally bad case) the gross flow-off the catchment during six years (from 1878 to 1883) varied from 10·0 to 19·0 per cent. only of the gross rainfall on the catchment. In the Hulsar tank at Bangalore the average flow-off of three years was only 14·0 per cent. of the total rainfall.

The Bombay Government published in the Administration Report of the Public Works Department (1890–91) a statement showing the results of run-off from the catchment areas of tanks in the Deccan. The statement dealt with observations recorded on nineteen tanks, and was based, as a rule, on the available monsoon rainfall, which was generally about 20 to 30 inches but fell in some cases to as little as 4 or 5 inches. The statement showed that out of these 114 observations there were :—

26	occasions	when	the	flow-off	was	less than 10 per cent. of the available rainfall.
44	„	„	„	„	between 10 and 20	
25	„	„	„	„	„ 20 and 30	
19	„	„	„	„	above 30	

The following facts are taken from the Bombay Irrigation Revenue Reports :—

Year.	Mashvad Tank. Catchment 484 square miles.		Ashti Tank. Catchment 92 square miles.		Ekruk Tank. Catchment 159 square miles.	
	Rainfall of the Monsoon Months in inches.	Percentage of Total Flow-off to Rainfall.	Rainfall of the Monsoon Months in inches.	Percentage of Total Flow-off to Rainfall.	Rainfall of the Monsoon Months in inches.	Percentage of Total Flow-off to Rainfall.
1884–85	13·40	9·5	abnormally small	1·9	20·39	17·76
1885–86	20·01	28·0	28·91	24·5	27·93	21·5
1886–87	28·88	15·5	29·21	16·5	33·05	22·6
1887–88	27·76	12·1	18·16	18·3	35·88	33·8
1888–89	21·00	10·5	13·89	11·7	24·75	19·8

The following facts are recorded in the report * of the Rushikulya project in Madras :—

Year.	Mahanuddee. Catchment 900 square miles.		Rushikulya. Catchment 850 square miles.	
	Rainfall of the Year in inches.	Percentage of Total Flow-off to Rainfall.	Rainfall of the Year in inches.	Percentage of Total Flow-off to Rainfall.
1868	44·1	5·0	44·1	6·3
1869	59·6	36·1	59·6	31·0
1870	55·5	51·3	52·7	74·2
1871	43·7	18·0	42·0	8·4

These facts show, generally, that the percentage of flow-off does decrease with the total annual rainfall, but that the same annual rainfall does not produce the same percentage of flow-off. This is because the

* Dated 8th March, 1882, by Mr. C. Vincent, Ex. Engineer.

rainfall is not distributed in the same way during the period of its fall. Thus, if in two years having the same total fall during the monsoon, the fall in one year is chiefly in June and July and in the other year is chiefly in August and September, the total flow-off will be greater in the second year, because the discharge from saturated land is far greater than that from dry land. Or if, in two such years, the fall of one year is equally distributed in gentle showers during the season, and, in the other year, the same total fall is recorded mainly in heavy falls lasting a short time, the flow-off will be far greater in the latter case, especially if the heavy falls occur when the catchment is damp. It follows from this that an estimate of flow-off to be accurate, must be based on an analysis of the monthly falls, or even on falls during shorter periods than that. The table on page 61 gives such an analysis for a certain tract. The following results were obtained * from an investigation of the rainfall on a catchment of about 100 square miles near Calcutta :—

Month.	Percentage of the Rainfall flowing off the Catchment during the Month.	
	In Years of ordinary Rainfall during the Month.	In Years of more than ordinary Falls during the Month.
June	5·0	10·0
July	10·0	20·0
August ..	25·0	50·0
September .	40·0	50·0
October ..	40·0	50·0

In all tanks and reservoirs there is a loss of water from leakage, absorption into the soil, and evaporation, which varies from as much as 10 feet in vertical depth of water annually to as little as 3 feet. In some cases there is a compensation for this loss in springs in the bed of the tank. The total actual loss from these causes has been measured in many instances, but it is always difficult to ascertain how much of it is due to each of the causes of loss. The loss from evaporation alone is believed never to exceed 0·4 inches a day in the hottest and driest weather in India. The loss from absorption varies greatly according to

* By the author.

the nature of the bed of the reservoir, but it may generally be taken at not more than half the loss by evaporation during the year, although, in the earlier months of the period when the flow-off the catchment is being impounded, it would be much greater; the loss by leakage depends entirely on local circumstances and is generally very small. The following statistics of the loss in different cases may be of use.

The loss by evaporation and absorption (which was probably very small) in the Red Hill tank at Madras, which has a water surface of 5 to 6 square miles, was gauged during a period of five years with the result that the average daily loss of that period was found to be 0·28 inches. The average * daily loss based on the facts of—

		inches.			inches.
4 Januaries	was ..	0·24	4 Julys	was ..	0·33
2 Februaries	„ ..	0·24	5 Augusts	„ ..	0·32
5 Marches	„ ..	0·26	1 September	„ ..	0·38
5 Aprils	„ ..	0·30	1 October	„ ..	0·27
5 Mays	„ ..	0·37	1 November	„ ..	0·27
4 Junes	„ ..	0·30	2 Decembers	„ ..	0·13

In the Ekruk tank in Sholapore, Bombay, having a waterspread of about 7 square miles, the loss from evaporation and absorption during the hottest part of the year (17th April to the 29th May) was found to average 0·384 inches a day, while the loss from the same causes, but with the addition of some leakage, during November to March, averaged 0·232 inches a day.

The loss in tanks in Rajputana is given by Mr. W. W. Culcheth as follows:—

1. Loss by evaporation and absorption in porous soils:—

Season.	Average Daily Loss in inches from		
	Evaporation.	Absorption.	Total.
During the irrigating season, October to March	0·15	0·05	0·20
„ hot „ April to June ..	0·29	0·17	0·56
„ rainy „ July to September	0·21	0·20	0·41
Average of the year	0·20	0·12	0·32

* 'Monograph on the Madras Water Supply and Irrigation Extension Project,' by Mr. C. Vincent.

These results are equivalent to a total vertical loss in the year from the surface of the tank of 6·15 feet from evaporation, 3·62 feet from absorption, or 9·77 feet in all.

2. The loss from absorption in porous soils is probably two-thirds of that from evaporation, but is reduced by springs to one-half.

3. When water is impounded in the monsoon months and drawn off for irrigation by the end of March the total vertical loss may be taken as 3 feet.

In the Pashan tank, near Poona, the average daily loss from evaporation alone has been gauged as 0·25 inches in October; 0·19 in November; 0·14 in December; 0·17 in January; 0·14 in February; 0·17 in March; 0·27 in April; 0·38 in May.

In the Nagpur reservoir in the Central Provinces the maximum loss recorded from evaporation and absorption in one day was 0·60 inches, and the average loss from both causes during the 142 days from 10th October to 9th June (that is the period of the year when the monsoon is absent) was 0·347 inches a day: the loss from evaporation alone being estimated to be 0·20 inches.

In the very dry climate of Upper Egypt the evaporation during the hottest months has been very carefully estimated to be 0·39 inches a day.

The quantity of water which is lost by absorption can be determined by no rule; it varies both with the nature of the soil on which a tank is constructed, or in which a canal is cut, and with the spring level of the subsoil. The loss is greater in running canals than in reservoirs. Mr. J. S. Beresford, who studied the matter closely in the North-west Provinces, came to the following conclusions:—

1. That loss by absorption is greater when a canal is in cutting than when it is in embankment.

2. That, when the other conditions are constant, the loss by absorption varies directly as the wetted perimeter of the channel.

3. That under ordinary conditions the loss by absorption between the head of a distributary and any point L miles from the head can be approximately ascertained by the formula

$$\text{Loss} = A\,L^{x},$$

where A is the loss actually ascertained by experiment in the first mile, and x, the power to which L is raised, varies from $\frac{5}{6}$ to $\frac{6}{7}$.

4. That there is more waste by absorption in village channels than in all other parts of an irrigation system.

The loss by absorption is much greater, as a rule, in new canals than in old ones, as the porous surface of an absorbent soil becomes staunched by the silt which is deposited on it and drawn into the interstices of the ground. This is of course more particularly the case when the water of the canal is much charged with silt, and will not occur when the canal carries clear water.

The extent to which this staunching action of silt may be carried is well illustrated by the filters of the Calcutta waterworks. The water is pumped from the Hoogly, which at times carries a large percentage of fine muddy silt, and is settled for 4 or 5 days in large settling tanks before it is passed, in a comparatively clear state, on to the filters which are constructed of layers of pebbles, gravel, coarse sand and fine sand in layers, the fine sand being on the top. At those times when there is much silt in the river these filters become so far choked with silt as to be almost water-tight against a head of 24 inches or so, and this staunching is almost entirely effected in the topmost half inch of the fine sand. When this half inch is removed, every fortnight or so, the filters again become efficient. The same action goes on in a canal, and, so far as may be, it is desirable to let the silt remain untouched in canals and distributaries where absorption is likely to occur.

The extent to which absorption may reduce the discharge of a canal is rarely appreciated. A small canal, called the Hathmati Canal, in Bombay, carrying an ordinary discharge varying from 20 to 100, and a maximum discharge of 191 cubic feet a second, has been gauged * for a series of years, and the results show that at least fifty per cent. of the discharge is lost by evaporation and absorption in the first ten miles, in which there is practically no irrigation. This is an extreme case but losses of from 10 to 40 per cent. between the head of an irrigation system and the fields actually watered are to be expected. On a sandy reach of the Patna Canal in Bengal, an exceptional opportunity once occurred for gauging the actual loss by absorption. The canal was new, the reach was 7 miles long, 69 feet base, and had about 4½ feet of water at one end, and 8 at the other (the water being impounded): the loss by absorption was found to be over 40 cubic feet a second. This has now been greatly reduced by silt deposited on the bed and banks of the canal.

The Nira Canal, near Poona in Bombay, has a total length of 101 miles, and has a head discharge of 455 cubic feet. Careful experiments †

* 'Bombay Revenue Report,' 1889–90.

† 'Report on the Nira Canal Project,' published by the Government of Bombay, 1892, page 12.

have shown that the average loss in the canal from evaporation, absorption, and percolation amounts to one cubic foot per second per mile, or 101 cubic feet per second altogether, which is 22 per cent. of the maximum discharge entering at the head. The results obtained for the loss by leakage in this canal, correspond very closely with those on the Mutha Canal in the same district, where the loss was found to be from 0·8 to 0·9 cubic feet per second per mile, the maximum head discharge being 412 cubic feet.

Some experiments were recorded * by Mr. Higham on the Bari Doab Canal in the Punjab, after it had been open for some 16 or 18 years, to determine the loss due to evaporation and absorption. Care was taken to get the canal into train, and to shut off all distributary heads and other sources of leakage. The first series of observations was made on the upper portion of the canal, 52 miles in length, between Madhopur and Chandeki, which runs in a light boulder soil. The velocities were carefully ascertained by suitable floats. The results were :—

Experiment.	Date.	Madhopur.		Chandeki.		Loss.	
		Mean Velocity.	Discharge.	Mean Velocity.	Discharge.	Volume.	Percentage.
		feet per second.	cubic feet per second.	feet per second.	cubic feet per second.	cubic feet per second.	
A	March 1 and 2	—	2009	2·68	1728	281	14·0
B	May 26 and 27	4·44	2142	2·93	1874	268	12·5
C	May 28 and 29	4·33	2036	2·79	1789	247	12·1
I	June 9 and 10	4·44	2165	2·77	1874	291	13·5

The second series of observations was made lower down the canal between Hibban and Gandian, a length of 63 miles, where the canal is in stiff soil. The results were :—

Date.	Hibban.	Gandian.	Loss.	
	Discharge in cubic feet per second.	Discharge in cubic feet per second.	Cubic feet per second.	Percentage.
31st July ..	289·4	243·2	46·2	15·9
2nd August	384·3	298·4	85·9	22·4

* Report dated 7th December, 1875.

At the same time observations which were recorded on two or three distributaries showed a percentage of loss, in those channels, varying from 20 to 30 per cent. of their discharges at head. These results, it should be remembered, were not on a new canal, but on one which had been so long in operation that all abnormal causes of loss had been removed. They are of great importance with reference to the extent of country which can be irrigated with a given supply of water and bear materially on the matter of the "duty" of water for irrigation, which will be treated in Chapter XV.

CHAPTER V.

STORAGE WORKS, RESERVOIRS, TANKS.

Madras Tanks—Rushikulya Project—Periyar Project—Cross Sections of various high Masonry Dams—Nira and Mutha Canals—Bhatgarh Reservoir—Conditions of Design of Bhatgarh Dam—Weight of Concrete in Bhatgarh Dam—Under-sluices of Bhatgarh Dam—Waste Weirs of Bhatgarh Reservoir—Head-works, Nira Canal—Ekruk Tank—Waghad Tank—Earthen Embankments—Grass Revetments in Tanjore—Failure of Embankments from Saturation—Statistics of the Principal Tanks in Bombay—Reservoirs in Egypt—Proposed Reservoirs in the Wady Raian, at Assuan, Kalabshah or Silsila on the Nile.

MADRAS and Bombay are the two provinces of India in which the demand for the storage of water is most apparent. In both cases the majority of the rivers have short courses, and the rainfall, which frequently falls in heavy but brief storms, passes rapidly away. In Madras the waters of the larger streams have been fully utilised in their deltas on the coast by large perennial irrigation canals, but in the higher ground, where such works are unsuitable, the water of the smaller streams is economised in a vast number of tanks, which are dotted about all over the face of the country. These tanks are being extended and improved by Government. The following description has been taken from the book of estimates and plans for these improvements.* The country is divided into "Basins" and "Minor Basins," according to the catchment areas of the streams and the tanks situated in them: the tanks are divided into groups and sub-groups for statistical and administrative purposes. Plate XIV. shows a portion of the Suruli Naddi group of the Suruliyar Minor Basin, which lies in the Upper Vigai river basin in the Madura district. In this case the minor basin contains an area of 512 square miles draining into the Vigai. The Suruli Naddi and its tributaries have their source to the east of the watershed of the general range of the Western Ghauts, and the discharge of the streams is fairly constant, as they draw their supply from mountains, 6000 feet above the sea, which are overgrown with impene-

* 'General Descriptive Memoirs of Irrigation Works in the Upper Vaigai River Basin,' Madras, 1887.

trable forests. The average annual recorded rainfall is 26 inches only in the centre of the minor basin, but in the neighbouring hills it is taken to be as much as 95 inches in the year. There are no less than 127 separate systems of irrigation within this minor basin, having a total irrigated area of only 17,996 acres. The system of irrigation is partly from channels which are led off from the streams by means of anicuts or weirs across the river, but largely from tanks which receive their supply mainly from the catchment area above them, but in some cases from the channels supplied by the rivers. Thus tanks Nos. 24 and 25 are small rain-fed tanks, but No. 27 is fed by the Viranvan channel which takes off above an anicut or weir across the river. Tank No. 29 is entirely rain-fed. In system No. 31—which is shown on a larger scale in the plate—the irrigation is mainly effected from the channel which is nearly four miles in length, but tanks 32, 33, 34 and 35, which are fed by the same channel, store water for use when the supply in the river is deficient. There are 966 acres of irrigation under this little system. The channel runs across the drainage of the country and diverts the rainfall of 11½ square miles into four tanks which are supplied with masonry sluices. These four tanks have a joint capacity of 25 millions of cubic feet, but, as they are filled and exhausted several times during the season, the annual storage, which is depended upon, amounts to nearly three times that quantity.

Plate XV. gives more detail of works Nos. 13, 14, 15, 16, and 17 of the general plan. No. 13 is a channel which takes off the river above an anicut, 306 feet in length, of which the details are shown. This channel supplies the three tanks from the river, and it also intercepts the drainage of 13½ square miles of country, which is either stored in the tanks or escapes through the sluices and surplus weirs which are constructed in them. The three tanks have a joint capacity of 66 million cubic feet, and the available annual storage is taken as 274 millions. Work No. 17 is a purely rain-fed tank having 12½ square miles of catchment. In all these small tanks it is assumed that each 200,000 cubic feet of available annual storage is sufficient for each acre of irrigation. In calculating the discharges from the catchment areas above the various weirs and tanks, the formula used was

$$\text{Discharge in cubic feet per second} = C M^{\frac{2}{3}} - c m^{\frac{2}{3}},$$

where C was taken as from 500 to 600 and c as 100, M being the area in square miles of the catchment, and m the area of the free basin of tanks which operate as moderators of the discharge.

Plate XVI. shows a reservoir project, now under construction, in the Ganjam district of Madras, where there is liability to scarcity and famine on account of uncertain rainfall. The project utilises the water of the two small rivers, Rushikulya and Mahanadi, both by direct draught on the supply in them, and by storing the water in two reservoirs constructed in the bed of the streams. The Bavancona Reservoir on the Mahanadi will be mainly supplied by a channel from the Gulleri river which has a catchment of 170 square miles. The waterspread of the reservoir will be about 4¼ square miles, the maximum depth will be 60 feet, and the contents will be 2457 millions of cubic feet, of which 2295 millions will be available for irrigation. The reservoir will be formed by an earthen dam, from 10 to 18 feet crest, with inside slopes of 2 to 1, and outside of 3 to 1, with a puddle wall in the centre and the inner slope revetted with rubble. The Soorada Reservoir on the Rushikulya, which will be formed by a similar dam of earth, 45 feet high, will have a waterspread of 7·14 square miles, and will contain 2160 millions of cubic feet: the catchment is 250 square miles. It is expected that the reservoir will fill twice in the year. The project provides for the irrigation of 120,000 acres in the tract of country lying between Aska and the Bay of Bengal: it is estimated that the minimum supply in the rivers can be sufficiently supplemented from the water stored in the two reservoirs to ensure a discharge of 1 cubic foot per second for every 100 acres irrigable during the irrigation season. The water from the reservoirs will be drawn off into the channels of the rivers below the dams, and, after flowing some distance, will be intercepted by the weirs at Goomsar and Jada and diverted into the canal, from which the irrigation will be effected by a series of distributaries.

One of the most interesting reservoir schemes in India is the Periyar project in Madras, which is now in course of construction. This striking work is designed to irrigate the district of Madura, in Southern India, where the rainfall is scanty and very uncertain, and where famines have frequently occurred. This district is at present watered by the Vigai river which draws its supply from a catchment area, lying on the eastern side of the Ghâts which separate the British territory of Madura from the independent Native State of Travancore. The supply in the Vigai river has been used for irrigation from time immemorial, and the river is crossed by many small weirs or anicuts, which divert the available supply into the small tanks which have just been mentioned: it has indeed been asserted that in an average year not a drop of the Vigai water reaches the sea, but the supply is most scanty and uncertain. At

the western side of the Ghâts, however, the rainfall is copious and secure; it averages about three times that of the Madura district and the discharge from the vast tracts of uninhabited jungle, which lie in the Travancore State, passes unutilised to the sea near Cochin, down the channel of the Periyar river, which at one portion of its course is within a few miles of one of the tributaries of the Vigai. The project for diverting the surplus waters of the Travancore jungles across the hills which intervene between the Periyar and the Vigai, has been put forward in various shapes since the beginning of the century, and is now being executed from the designs of Col. J. Pennycuick, R.E.* A general map of the project is given in Plate XVII., and some of the details of it are shown in Plate XVIII. The main feature of it is a reservoir on the Periyar river, containing 13,300 millions of cubic feet of water, of which 6815 millions will be available for irrigation between the level of the sill of the outlet and that of full supply. This reservoir will be formed by a concrete dam about 1300 feet in length, and 155 feet in height from the bed of the river to the crest, above which there is to be a parapet 5 feet high: the section of the dam is shown on the plate. The water impounded in the reservoir will be drawn off into a tributary of the Vigai river by a tunnel, 6650 feet in length, having an area of 84 square feet and a slope of one in seventy-five. From the mouth of this tunnel the water from the Periyar Reservoir will flow down the river channel, for a distance of 86 miles, until it reaches a point in the plains of Madura where it can be conveniently distributed for irrigation by means of a weir across the river and an ordinary system of canals. There will be various regulating works in the channel of the stream between the tunnel and the point of distribution. The area which the project is expected to irrigate is 140,000 acres.

The catchment area above the dam on the Periyar is about 300 square miles in extent, and the rainfall on it, which is well distributed, is stated to be more than 120 inches in the year. The reservoir will have a waterspread of about 12 square miles, and, although the available impounded supply will be only 6815 millions of cubic feet, it is calculated that the total amount of water which can be drawn from the reservoir during the year, with the help of the supply in the Periyar river, will be about 30,000 millions, which will allow rather more than 200,000 cubic feet for each irrigable acre. The loss by evaporation is assumed at 3230 millions of cubic feet, and 500 millions are allowed for filling up the dry beds of the rivers after the hot season. It seems

* From whose report most of this description is taken.

doubtful whether this provision will prove sufficient to cover the heavy loss from evaporation and absorption in the 86 miles of river channel which are traversed by the water between the tunnel and the head of distribution; and it seems probable that there may be further loss on this length of channel owing to the fact that numerous old weirs exist which will render it possible to intercept for local purposes the supply which is hypothecated for the land in the plains below.

The construction of this great work is being carried on under most disadvantageous circumstances: the site of the Periyar dam is in the heart of a most intensely unhealthy district, where work is only possible during a portion of the year.

Plate XIX.* gives the cross sections of the four most important masonry dams in India, drawn to the same scale. It also shows other well-known high masonry dams, but these, it will be noticed, are not all to the same scale, so a comparison of them is rendered a little difficult.

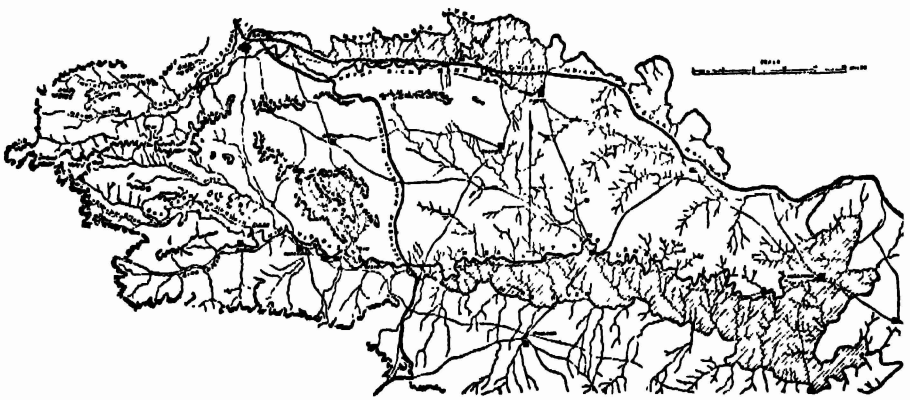
The reservoirs and tanks in the Bombay Presidency are in all cases constructed in hilly ground. They vary in area from 10 square miles of waterspread down to 50 acres, and in capacity from 5000 millions to 15 millions of cubic feet. The majority of the reservoirs are constructed with earthen embankments, which vary in maximum height from 95 feet down to 29 feet, but there are five which are formed by masonry, or concrete, dams which vary in height from 120 feet to 60 feet. The two most important of these are Lake Fife and the Bhatgarh reservoir near Poona, which will now be described. The Mutha and Nira rivers† in the Poona district of Bombay are fed from the Ghâts, where there is an unfailing rainfall of some 200 inches, and they can always be depended upon to provide an abundant supply of water during the monsoon months, although in the valleys in the eastern portion of the district in which the rivers run, the rainfall is very uncertain, and subject to frequent failure. The necessity of reservoirs in the valleys of these rivers, to store the monsoon supplies, as a protection against famine, was recognised before Colonel Fife first brought forward, in 1863, the project for the Mutha Reservoir (Lake Fife) and the Mutha Canal which he afterwards carried to completion. This reservoir is formed by a masonry dam of uncoursed rubble nearly 3700 feet long and 98 feet high, in the loftiest part, above the river bed: the waterspread of the reservoir is

* This plate is taken from the 'Report of the Nira Canal Project,' published by the Government of Bombay.

† This description of the Nira Canal and Bhatgarh Dam is taken largely from the 'Report on the Nira Canal Project,' published by the Government of Bombay in 1892.

about six square miles, and it contains nearly 5000 millions of cubic feet of water, of which rather more than 3000 millions are available for irrigation.

The Nira Canal system as actually carried out is substantially the project which was prepared by Mr. Whiting and sanctioned in 1881. The works are now practically completed: the main features of the system are shown in the following sketch:—



NIRA AND MUTHA CANALS, WITH THE BHATGARH RESERVOIR AND LAKE FIFE.

They consist of:—

I. The Bhatgarh Reservoir on the Yelwandi river.

II. The Vir Basin formed by the weir on the Nira river at Vir.

III. The main canal on the left bank of the Nira river.

The Nira river, during the monsoon months of June to October, discharges much more water than is needed for the full supply of the canal, but after October the supply rapidly decreases and from January to June there is practically none at all. In order, therefore, to secure an unfailing supply throughout the year the Bhatgarh Reservoir has been constructed: it contains a gross volume of 4642 millions of cubic feet of water when full, of which 4148 millions of cubic feet are available for irrigation. The water from the reservoir is drawn off into the rocky bed of the Nira and flows down it to the basin, in the bed of that river, which is formed by the head-works of the canal. These are constructed across the river at Vir for the purpose of diverting the supply into the canal. The Vir Basin impounds a certain quantity of water which is also drawn upon for irrigation. The canal, which follows a contour on the left bank of the Nira river, commands an irrigable area, between itself and the river, of about 136,000 acres, of which it is estimated that 56,640

acres can be irrigated by the available supply. The canal is 101 miles in length and is provided with 110 miles of distributary channels.

The catchment area of the Bhatgarh Reservoir is 128 square miles with an annual rainfall varying from 250 inches in the Ghâts to 40 inches at the dam site. The maximum run-off originally assumed in the case of Lake Fife (which has a catchment similar to that at Bhatgarh but 62 square miles larger in area) was half an inch an hour, and only on one occasion since the lake was completed has the flood been known to approximate to that figure. For the smaller area at Bhatgarh the maximum run-off was assumed to be $\frac{5}{8}$ of an inch per hour, which is equivalent to 51,600 cubic feet per second from the catchment of 128 square miles: the waste weirs have been designed to permit of the escape of rather more than this quantity from the reservoir.

The masonry dam which forms the reservoir is built on the Yelwandi just above the point where it joins the Nira river. This site was selected because the foundation was suitable for a large dam and the catchment was ample to provide the supply required, and was, at the same time, not so large as to demand excessive escapes: the site also offered advantages for the construction of suitable waste weirs and for the supply of materials for the dam.

The dam (Plate XX.) which is built of masonry and concrete in accordance with the specification given in Appendix XII., is 3020 feet long with a maximum height of 127 feet above the lowest foundation and 103 above the bed of the river: the width at full supply level is $12\frac{1}{2}$ feet and the maximum width of base is 76 feet. There are two waste weirs, one at each end of the dam. A roadway, 11 feet in the clear, runs along the top of it and is carried over the waste weirs on piers and arches. The clear length of water-way of the two waste weirs is 810 feet, which is calculated to discharge the maximum flood (51,600 cubic feet per second) with rather less than 8 feet head on the crest.

The design of the dam was based on the conditions that the intensity of vertical pressure was not to exceed 120 lbs. per square inch in any part; that the resultant pressure was to fall within the middle third of the base in any portion of the section and that the average weight of the material of the dam was to be taken at 160 lbs. per square foot. This may seem a high figure, but it was found that the actual weight of the structure was quite equal to it. Some of the stone used weighed as much as 190 lbs. to the cubic foot and it averaged 183 lbs.; and concrete made of gravel, metal, and mortar was 154 lbs. to the

cubic foot. It may be noted that the weight assumed in the calculations of the Tansa Dam of the Bombay Waterworks was 150 lbs. per cubic foot; in the case of the Quaker Bridge Dam, which is to be built for the water supply of New York, the figure taken, which was determined by experiment, was 156·25 lbs.; in the Vyrnwy Dam the actual weight of the materials is 160·8 lbs. per cubic foot; and in the Ternay Dam in France the assumed weight was as high as 167 lbs. The figure of the cross section of the dam, as shown in Plate XXI., was worked out, by a graphic method, to fulfil the conditions stated above: the figures at the margin of the section show the intensity of pressure per square inch calculated from the formula *

$$p = \text{intensity of pressure} = \frac{R}{A}\left(1 + \frac{6v}{x}\right),$$

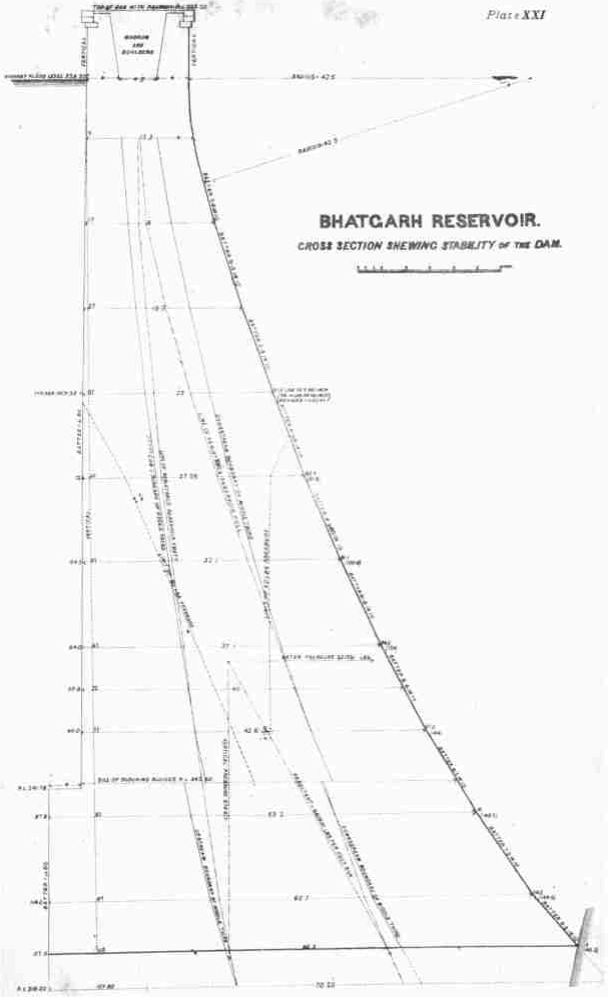
where R is the vertical component of the resultant of the weight and water pressure; A the area of the base at each section considered; x the width of the base in question; and v the distance of the line of resistance from the centre of the base. The figures in brackets show the intensity of pressure calculated by M. Bouvier's theory: these are considerably in excess of the former.

The mortar used in the work is known to have a crushing strength, when one year old, of fully 700 lbs. on the square inch: it will be seen from the diagram on Plate XXI. that the maximum pressure, which occurs at the up-stream toe when the reservoir is empty, is 117·5 lbs. per square inch, so the factor of safety is a high one. Some existing masonry dams in Europe have higher pressure than will ever be reached in the case of the Bhatgarh Dam: thus:—

Villar Dam	(Spain) ..	150 lbs	per square inch	on up-stream	toe
Gileppe „	(Belgium) ..	150	„	„ down-stream	„
Alicante „	(Spain) ..	171	„	„ „	„
Bau „	(France) ..	155	„	„ up-stream	„

In the original design of the Bhatgarh Dam it was proposed to construct it entirely of rubble masonry. The excellent results which were obtained, however, with samples of concrete used in the weir at Vir, led to the substitution of concrete for rubble masonry in the hearting of the Bhatgarh Dam. The result of a series of experiments with blocks (10 inches × 10 inches × 15 inches) of concrete at Vir showed that the average crushing weight was 400 lbs. on the square inch: the concrete at Bhatgarh gave a corresponding result of 375 lbs. So it was determined

* This is another form of the formula given in Appendix XI., para 3.


BHATGARH RESERVOIR.
CROSS SECTION SHEWING STABILITY OF THE DAM.

to employ concrete, with blocks of rubble imbedded in it, where the pressure did not exceed 60 lbs. on the square inch. The boundaries of the 60 lbs. pressure are shown on the plate. The base of the dam, where the pressure exceeds 60 lbs. on the square inch, is built of uncoursed rubble between faces of hammer-dressed block-in-course masonry varying from 3 feet to 15 inches in thickness. In laying the foundations, the rock, at the down-stream toe, was dressed throughout with a slope downwards towards the centre of the dam; and, similarly, at the up-stream toe, it was dressed so as to be generally at right angles to the up-stream batter of the face, which is 1 in 50. The centre portion of the foundation was blasted out, so as to present a rough base everywhere.

The dam is pierced in the centre (Plate XX.) by fifteen under-sluices, each 8 feet by 4 feet, which provide an escape for the earlier floods of the year before it is necessary to close the gates in order to fill the reservoir. The object of these under-sluices is to prevent the deposit of silt in the reservoir by allowing the floods to pass through them at a low level instead of over the waste weirs. As there is a danger of the sluices being choked by timber and brushwood, so that they could not be closed when necessary, there are screens in front of them formed of rails placed horizontally 1 foot apart. These rails are only 2½ feet from the sluice: it would have been better if they had been placed at a greater distance in front. The rails have proved to be an ample and sufficient protection against heavy timber, but brushwood accumulates on the rails, and on one occasion prevented for a time one of the gates from being quite closed. It is found that, after the first heavy flood in July, the river can be discharged through the fifteen sluices with a head varying from 4 to 15 feet, and that when it falls to 8 feet it is possible to clear away the accumulation of brushwood. The fact that it will always be possible to clear the protective screens before it is necessary to finally close the gates for the season, considerably reduces the risk of failure to close the gates.

The question of the efficiency of the under-sluices in prolonging the life of the reservoir has been a matter of controversy. On the one side it is held that, as the water must head up to 8, 15, or sometimes even 30 feet above the sluices, in order to pass the early floods, the reduction in the velocity of flow in the reservoir, owing to the greatly increased section of waterway, must be so great that a large proportion of the silt held in suspension must, in any case, be deposited; and it is said that, although the sluices will certainly have some effect in the direction indicated, that effect will be comparatively small, and not worth the expense and risk which the sluices involve. On the other hand, the

arguments * in support of the theory that the sluices will be effectual in prolonging the life of the reservoir are as follows :—"The year 1890 was an average one as regards the river discharge. The quantity of water gauged to have passed through the sluices amounted to 30,000 millions of cubic feet, or nearly six times the contents of the reservoir. Experiment has proved that during the first monsoon floods the silt held in suspension is quite 1 part in 100. If there had been no sluices, the reservoir would have filled when the floods were most heavily laden with silt, and subsequently the water would have been discharged by the waste weir after the greater proportion of silt had been deposited in the lake. It is therefore probable that silt to the extent of at least 1 in 500 would have been left in the reservoir, which at this rate would be silted up to waste weir level in eighty years. The sills of the sluices are 12 feet above the bed of the river, the fall of which is 5 feet a mile. From observation it is found that in ordinary years the floods will be discharged with an average head of 15 feet, and water will be ponded up for a distance of three miles above the dam ; consequently a certain proportion of the heaviest silt will still be left in the reservoir, owing to the velocity of the floods being checked, but the distance from the sluices being so short, there is not sufficient time for the silt to be deposited, and the greater portion will be carried off. The estimate that two-thirds of the silt that would otherwise be deposited in the reservoir will be passed through the sluices is probably a low one. The fact also remains that the area of the backwater above the dam during the monsoon, when the river is discharged with an average head of 15 feet, is less than one-thirtieth of the whole area of the reservoir, and therefore, at the time when the greatest amount of silt is held in suspension, twenty-nine thirtieths of the whole area is uncovered, and consequently no silt can be deposited there. The minor danger, therefore, only remains from pebbles, gravel, and heavy particles left at the point where the check must occur. Judging from the way in which the large scouring sluice in the main weir at Vir has acted, it appears more than probable that eventually, when the basin has silted up to the sill of the sluices at Bhatgarh, a new river-bed will be formed, extending possibly for 6 or 7 miles above the dam, and an equilibrium will be established, the silt deposited in one season being brought forward and carried along the new channel till it is passed through the sluices, the result being that silting up will be confined to the area up to the

* Taken from the report quoted in the foot-note, page 75.

NIRA CANAL.

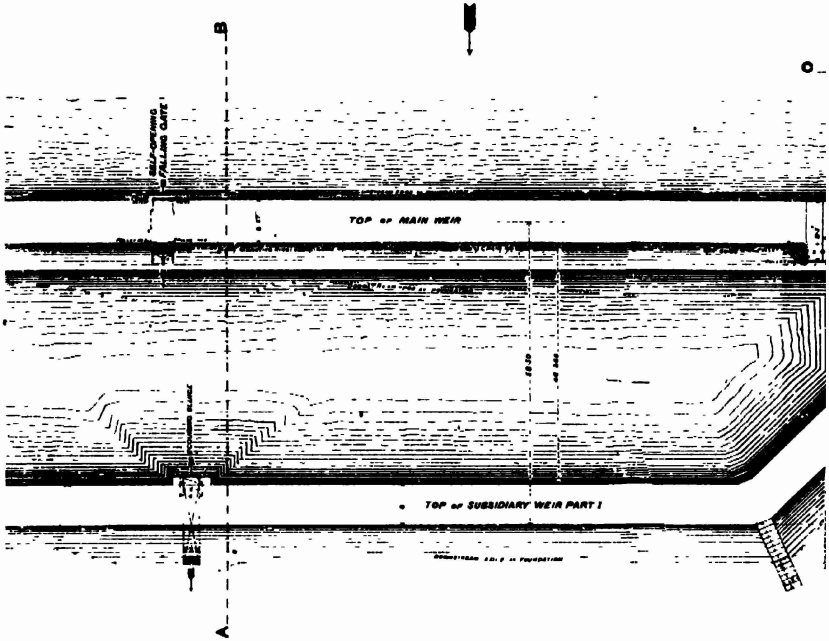
HEAD WORKS.

AT

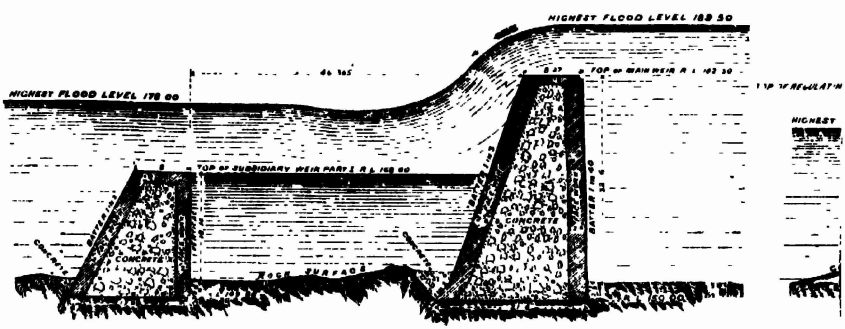
VIR-WADI.

V I R N A L A

PLAN



SECTION ON A.B.



15-foot contour, and the main body of the reservoir will always be kept clear."

The waste weir is divided into two portions (Plate XXII.): the northern portion has forty-five vents and the southern one thirty-six vents, each 10 feet wide, fitted with automatic gates, so that the water can be impounded up to the level of the top of the gates, which is 8 feet above the waste weir crest. A description of these automatic gates is given in Chapter XI. The two weirs are capable of discharging, as mentioned above, rather more than 51,600 cubic feet a second.

The head-works of the canal on the Nira river are shown on Plate XXII. They consist of a main weir, two subsidiary weirs, and a head-sluice or regulator for the canal. The weir, which is built on the rocky bed of the river, extends across both the Nira river and the Vir Nala, which joins the main river at this point. The main weir has a clear length of overfall of 2273 feet, the crest being 42 feet above the original bed of the river. The breadth of the weir at the crest level is 9 feet, and at river bed 26 feet. The batter of the upstream face is 1 in 40, and of the downstream face 1 in 3 for a height of 29 feet from the top, and 1 in 2 below the foundations. The base of the weir, up to 26 feet from the crest, is constructed of heavy rubble masonry, the rest being of concrete laid between two faces of rubble, 2½ feet thick on the downstream, and 2 feet on the upstream face. The crest is curved at the upstream edge, and covered with rubble paving 9 inches thick.

There are two sluice openings in the curved portion of the weir which tend to keep a clear channel in front of it: they are 8 feet by 4 feet with sills 9½ feet below the crest level: they are closed, when the floods subside, by means of needles. There is also a scouring sluice 8 feet by 4 feet, with a falling gate in the centre of the weir across the Vir Nala. The under-sluices—if they can be so called—in this weir are remarkably small; there are only two sluice gates, each 3 feet by 4½ feet, with sills 12 feet below the weir crest, and 3½ feet below the gates of the canal head-sluice. They are said to have proved effective, but it is admitted that they ought to have been larger.

The canal itself follows a contour more or less on the sloping ground along which it runs: it crosses heavy drainages for which no less than 117 drainage works—aqueducts, culverts, and superpassages—have been constructed. One of these is illustrated in Plate LXXVIII., page 206.

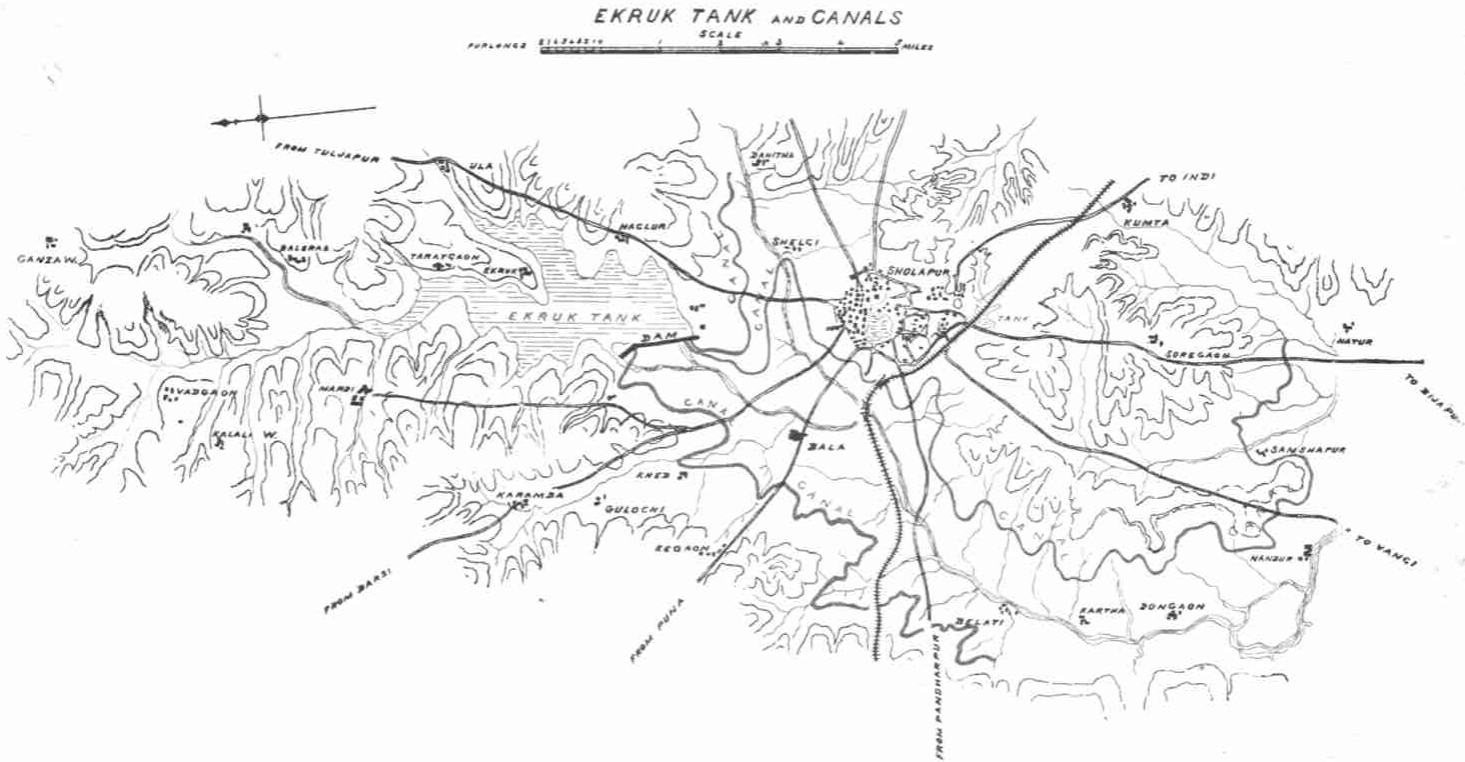
Plate XXIII. shows the Ekruk Tank in Sholapur, which is formed by an earthen embankment 7000 feet long and 76 feet in maximum height. The catchment area is 159 square miles, the waterspread

7¼ square miles, the capacity 3310 millions of cubic feet, and the maximum depth 60 feet. This is one of the largest tanks in Bombay. It supplies three canals, two are at a high level, on the right and left bank of the river respectively, and one is a low-level canal on the left bank: these canals are about 50 miles in length, and they command rather less than 18,000 acres of land.

The Waghad Tank (Plate XXIV.) and the system called the Kadwa River Works connected with it, is an example of the ordinary irrigation works in the Bombay Presidency. The Waghad Tank has a catchment area of 28 square miles only, and a capacity of 605 millions of cubic feet: it is formed by an earthen embankment a little more than 4000 feet long, and 95 feet in maximum height. The water in the tank is drawn off, when required, into the Kolwan river below it, and is diverted into the canal by a weir across the river at Palkhed. A supply is also drawn into the canals by the weir across the Banganga river at Ojhar Tambat: it has been proposed to construct a reservoir on this river also. Plate XXIV. gives the plan and longitudinal section of the embankment and the contours of the tank, also a cross section, showing the embankment itself and the outlet sluice. The bye-wash, or waste weir, is 650 feet long, and carries 5 feet depth of water as a maximum: it is constructed on the rock on the left flank of the weir.

Earthen embankments of great height need to be founded with at least as much care as those of masonry. The surface soil should in all cases be removed, and the nature of the strata below should be carefully examined by borings to see that the soil is homogeneous, sufficiently impermeable to water, and capable of bearing the pressure which will be placed upon it. If permeable strata are found at the site of the proposed embankment, they must either be removed, cut off by curtain walls of puddle, or sealed over to prevent percolation and upward saturation of the bank. The foundation should be benched so that the new soil of the embankment rests on horizontal tables, and the benches should be so cut that no step, running at right angles to the axis of the embankment, is continuous across the width of foundation. The dimensions of earthen embankments of tanks and reservoirs in India follow no fixed rules, but generally inner slopes of 2½ or 3 to 1, and external slopes of 1½ or 2 to 1 are used, with a width of bank at the water-line equal to the total depth of water against the bank at the point. Puddle cores are not commonly employed. It is desirable to use, as far as possible, the same kind of soil throughout an embankment, so as to ensure equal settlement, and to lay the material in horizontal and shallow layers, so

Plate XXIII


EKRUK TANK AND CANALS
SCALE
FURLONGS
MILES
FROM TULJAPUR
ULA
DANITHA
TO INDI
KUMTA
GANZA W.
BALERAS
TARATGAON
EKRUK
NAGLURI
SHELGI
SHOLAPUR
EKRUK TANK
DAM
CANAL
TANK
SOREGAON
NATUR
TO BIJAPUR
VADGAON
MARDI
KALALA W.
BALA
SAMSHAPUR
KHED
KARAMBA
GULOCHI
KEGAON
TO VANGI
NANDUR
FROM BARSI
FROM PUNA
BELATI
KARTHA
DONGAON
FROM PANDHARPUR

that it may be well consolidated as the work proceeds. Earthen embankments rarely, if ever, fail from direct hydrostatic pressure, but, usually, either from the washing of waves cutting through a too narrow crest; or, more commonly, from saturation of the bank and consequent slips in the embankment. The first danger is prevented by raising the crest of the embankment well above the maximum water-line, and by revetting it securely with some strong material—rubble stone if possible. It is desirable to keep the crest of the embankment at least 6 feet above the highest water level, and when the length of the reservoir is in the direction of the highest winds this may be advantageously increased. Stone revetments are made from 2 feet to 4 feet in thickness, and usually cover the area of the bank lying between low water level and the crest of the bank. In some tanks in Madras a grass or reed revetment is used as shown in the sketch on next page.

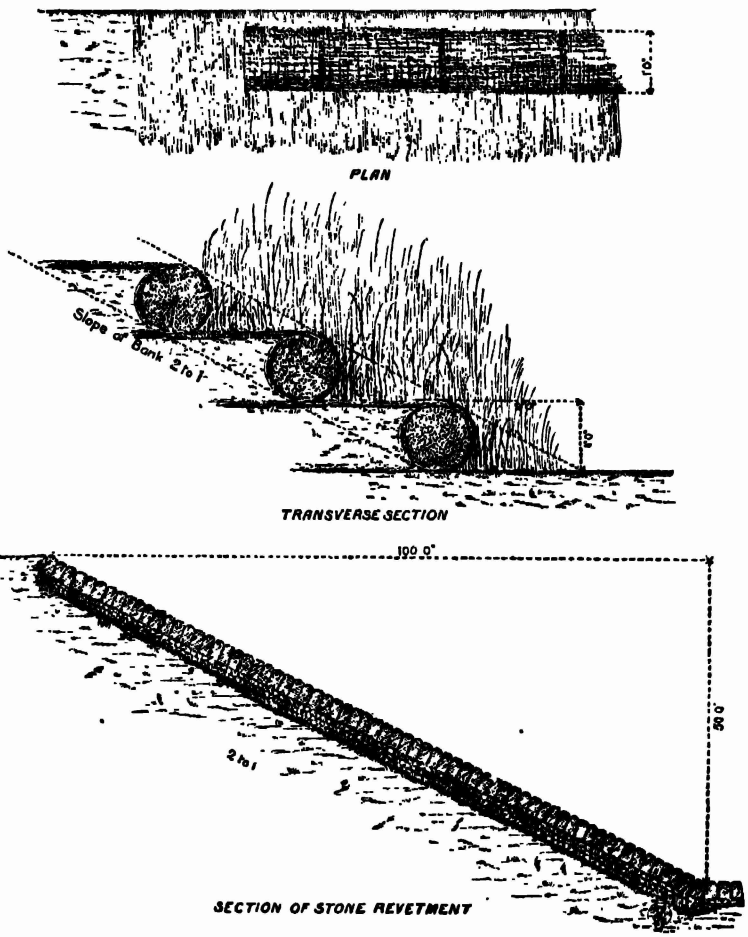
This form of revetment is described * by Col. Rundall, R.E., as follows:—"The material is a reed which grows on the margin of rivers or on the islands subject to inundation and generally in any marshy locality. Like all of its species it grows in joints, reaching a height of sometimes 10 or 12 feet, and at every joint is an eye, from which, when buried in the soil, a fresh plant will spring. The mode of construction is as follows:—The reed is first tied up into rollers or fascines about 1 foot in diameter and 10 to 20 feet long, a layer of reed is then laid transversely to the line of bank, and on this the roller is placed, the root end of the reed being inwards; the upper end is then folded over the rollers; as soon as a sufficient number of the latter have been laid lengthwise along the top of the bank, the whole is covered over with soil, and is well rammed or trodden down, and so the first step in the bank is made. Immediately above and behind the front roller another transverse layer is placed, and on this a fresh line of fascines is laid, over which the ends of the transverse layer are again turned and covered with earth, and so the process is repeated until the revetment has reached the required height. When completed it presents the appearance of a series of steps; it is then watered regularly once or twice a day, according to the season or the state of the weather, and after a few days, the eyes at the joints of the reeds begin to shoot, and in a short time a forest of reeds springs up and presents an impenetrable barrier to the action of any ordinary wave. This kind of revetment admits of earth and sand being retained at a steeper slope than would otherwise be possible. By this simple expedient the rivers in

* 'Lectures on Irrigation Works in India,' by Col. T. H. Rundall, C.S.I., R.E.

the Tanjore Delta are entirely regulated, there not being a stone procurable within many miles."

The saturation of an earthen embankment may occur either by water finding its way into the interior of the bank through the surface of the inner slope, or by water being forced up into it from below: the latter event is more liable to occur when the embankment stands on

GRASS REVETMENTS IN TANJORE.



rock which may have fissures in it. In either case the result may be that the interior or base of the bank becomes softened and is unable to withstand the weight, both of the water and of its own mass, and the bank settles, or, may be, slides horizontally on its base and a breach occurs. To prevent the saturation of the bank from its own surface, the best plan, of course, if it be feasible, is to make that surface impermeable to water by covering it with a watertight layer: that plan

must be more efficient than inserting an impermeable diaphragm (like a puddle wall) in the centre of the embankment, because it leaves the whole embankment behind it available to resist pressure, whereas, in the case of the puddle wall, only half the embankment is efficient if the half on the water side is supposed to be saturated. It is for this reason that some engineers prefer to place puddle on the inner slope rather than in a puddle wall; but the objection to the system is that, on the surface, even when protected by rubble pitching, the puddle is liable to crack during the dry season, when the water is low, and fail to be watertight when it rises; but a puddle wall, as it lies in the centre of the bank and is protected from the weather, is more certain to remain in a watertight condition.

Saturation of an earthen embankment, founded on very hard soil or rock, by water forced up into it from below through cracks and fissures, may reduce the lower stratum of an embankment to a state of muddy sludge on which the upper part, which might be quite sound in itself, would slide. In one such case of an earthen embankment over 90 feet in maximum height, it was proposed to deal with it in the following manner:—A concrete wall was to be constructed along the axis of the embankment founded 4 feet into the rock, the wall having a crest width (at H.W.L.) of 2 feet, and a batter on each side of 1 in 6 down to 16 feet above foundation level: the surface of the rock on the downstream side of this wall was first to be cut into a series of horizontal benches, so that the embankment should not lie on a sloping surface, and then to be cut into a series of longitudinal and cross drains covered with thick stones, which were to intercept the water rising from below and drain it off below the outer toe of the embankment: there were also to be two other longitudinal walls, founded 3 feet below the rock surface and projecting 5 feet above, one of these was to be at the outer or downstream toe of the embankment, and the other about midway between that wall and the axis of the embankment. In this case the object was to place the downstream half of the embankment on a well-drained platform, and to protect it from all percolation, either through the embankment itself or from below, while the two lower walls were to oppose any movement of the base of the bank. Provided that a really sound foundation can be obtained earthen embankments up to 60 feet in height present no difficulties or dangers, but above that height special precautions are necessary, and a most thorough investigation of the nature of the foundation is essential.

The following statistics of the principal tanks in Bombay are taken from a statement issued by Government in 1882:—

BOMBAY TANKS AND RESERVOIRS: CAPACITY, WATERSPREAD, AND FLOW-OFF.

Name of Work.	Area of Catchment Basin.	Average Annual Rainfall.	Fall of River above the Dam.	Estimated Total Yield of Catchment.	Capacity of Tank.				Net Area Irrigable from the Tank.	Cost of Dam, Waste Weir, Outlets and Land per million cubic feet of Capacity above Sluice-level.	Water-spread of Tank at Full Tank Level.
					Total.	Above Sluice-level.	Estimated Loss by Evaporation.	Available for Irrigation.			
	square miles.	inches.	feet per mile.	percentage of total rainfall.	millions of cubic feet.	millions of cubic feet.	millions of cubic feet.	millions of cubic feet.	acres.	rupees.	millions of square feet.
Tanks with Earthen Embankments.											
Mukti Tank ..	50·0	20·9	19	25	342·4	342·4	77·6	264·8	10,000	679	22·177
Mhasva „ ..	14·0	..	22	..	160·9	158·5	27·5	131·0	3,912	415	18·348
Sirsuphal „ ..	23·0	20·5	20	25	367·0	365·0	73·0	292·0	2,500	320	36·000
Matoba „ ..	10·0	15·3	32	25	230·0	229·0	42·0	187·0	7,133	513	21·000
Bhadalwadi „ ..	23·0	22·9	23	25	223·0	222·0	32·0	190·0	1,617	506	15·000
Ekruk „ ..	159·0	31·6	11	25	3330·0	3310·0	777·5	2532·5	16,784	232	198·232
Ashti „ ..	92·0	38·2	12	25	1550·0	1348·0	232·2	1186·0	15,000	267	123·296
Nehr „ ..	60·0	28·4	24	25	522·6	489·8	65·9	423·8	10,846	666	29·490
Pingli „ ..	20·0	23·0	31	25	200·8	195·2	40·9	105·8	5,332	919	15·220
Maini „ ..	54·0	24·2	20	25	195·3	188·6	33·1	155·5	3,364	881	16·570
Waghad „ ..	28·0	54·3	61	25	624·7	605·5	71·1	534·4	26,552	269	33·900
Tanks with Masonry Dams.											
Mutha Canal Reservoir	196·0	..	6·0	..	4911·0	3161·0	430·0	2731·0	66,147	544	154·000
Bhatgarh Reservoir, Nira Canal	128·0	145·0	5·0	..	4641·7	4638·3	365·4	4148·0	279,680	354	156·116
Muchkundi Tank ..	26·0	23·5	17·10	25	767·2	680·7	127·8	507·8	11,520	98	46·119
Mhasvad „ ..	508·0	22·8	12	10	3072·1	2632·7	349·7	2283·0	201,922	304	174·840

BOMBAY TANKS AND RESERVOIRS: DAMS, WASTE WEIRS, MAXIMUM DISCHARGE.

Name of Work.	Length of Dam.	Maximum Height of Dam.	Width of Crest of Dam.	Top of Dam.		Waste Weir.		Outlet Sluices.		Pitching.	
				Above Full Tank Level, i.e. above Level of Waste Weir Crest.	Above Maximum Flood Level in Tank.	Length of Weir.	Discharging Capacity of Waste Weir.	Depth of Sill below Full Tank Level.	Maximum Discharge.	Width of Pitching measured vertically.	Maximum Thickness.
	feet.	feet.	feet.	feet.	feet.	feet.	cubic feet a second.	feet.	cubic feet a second.	feet.	inches.
Tanks with Earthen Embankments.											
Mukti Tank	3,000	65·0	10	12·9	7·5	1,590	32,265	41·0	72·9	34·3	12
Mhasva „	1,494	44·0	10	10·1	6·0	300	9,034	22·0	71·4	41·2	15
Sirsuphal „	2,188	54·3	4	11·0	6·0	300	18,000	31·0	56·0	49·0	14
Matoba „	6,095	48·4	6	9·0	6·0	600	10,000	29·0	54·0	43·0	12
Bhadalwadi „	2,590	55·1	3	11·0	6·0	550	20,000	35·0	62·0	48·2	12
Ekruk „	6,940	75·7	6	17·0	7·0	750	43,763	38·3	621·0	73·7	24
Ashti „	12,700	58·0	6	12·0	5·0	800	48,000	22·0	247·0	34·0	12
Nehr „	4,820	74·0	8	14·0	7·7	700	38,720	31·0	172·0	45·0	12
Pingli „	5,553	53·5	6	9·0	6·0	750	12,862	29·0	119·0	36·0	12
Maini „	3,370	57·3	3	13·0	8·0	600	24,000	31·2	86·0	..	12
Waghad „	4,162	95·0	6	12·0	7·0	650	18,069	48·0	222·0	55·0	9
Tanks with Masonry Dams.											
Mutha Canal Reservoir	3,687	97·8	14·5	11·0	6·0	1,393	62,000	29·0	1411·0		
Bhatgarh Reservoir, Nira Canal	3,129	101·0	13·6	8·0	3·0	1,400	50,000	83·0	2103·0		
Muchkundi Tank ..	421	60·0	6·0	5·7	0·0	500	16,600	24·30	55·4		
Mhasvad „ ..	9,080	79·8	8·0	13·0	7·0	3,000	235,545	24·0	531·0		

The Bhatgarh reservoir in Bombay, which contains an available volume of 4638 millions of cubic feet, is, at present, the largest reservoir in India, but it will be superseded in a short time by the Periyar Reservoir in Madras, which will have an available volume of 6815 millions of cubic feet. But these works, great as they are, sink into insignificance when they are compared with the reservoirs which are under contemplation in the valley of the Nile. The summer supply of the Nile is but barely sufficient for the area of "*sefi*" or perennial crops which are now cultivated in Egypt, and this area might be largely increased if water were available to irrigate it: at certain times the whole summer volume of the Nile is utilised for irrigation, and it has been estimated that an additional discharge of 12,260 cubic feet a second (30 millions of cubic metres a day) for sixty days is required for the extension of the area under cultivation of summer crops in Egypt up to a point to which it is desirable to increase it, and that such an additional supply of water would increase the value of the produce of Egypt by about 2,500,000*l.* a year. The only possible means of increasing the summer supply is by constructing storage reservoirs, either in the Nile Valley itself or in the desert which borders it. Several projects have been suggested for such works. These have been subjected to preliminary investigation by the

Site of Reservoir.	Cost per million cubic feet of available supply.	Volume in the Reservoir available for irrigation.	Estimated Cost in Egyptian Pounds.*	Situation.
	£	millions of cubic feet.	£	
Wady Raian	20·9 11·7	70,600	1,479,247† or 827,000‡	In the desert beyond the Nile Valley, about eighty miles above Cairo.
Assuan ..	10·5	91,800	968,276	In the Nile Valley, immediately above the first cataract at Assuan.
Kalabshah ..	16·8	61,100	1,031,644	In the Nile Valley, thirty-three miles above the first cataract at Assuan.
Silsila	20·0	95,300	1,905,006	In the Nile Valley, forty-four miles below the first cataract at Assuan.

* The Egyptian pound is worth slightly more than the English pound sterling.

† Mr. Willcocks' estimate. ‡ Col. Western's estimate.

engineers * of the Egyptian Government, and the projects enumerated on the preceding page are under consideration as being the most promising ones.

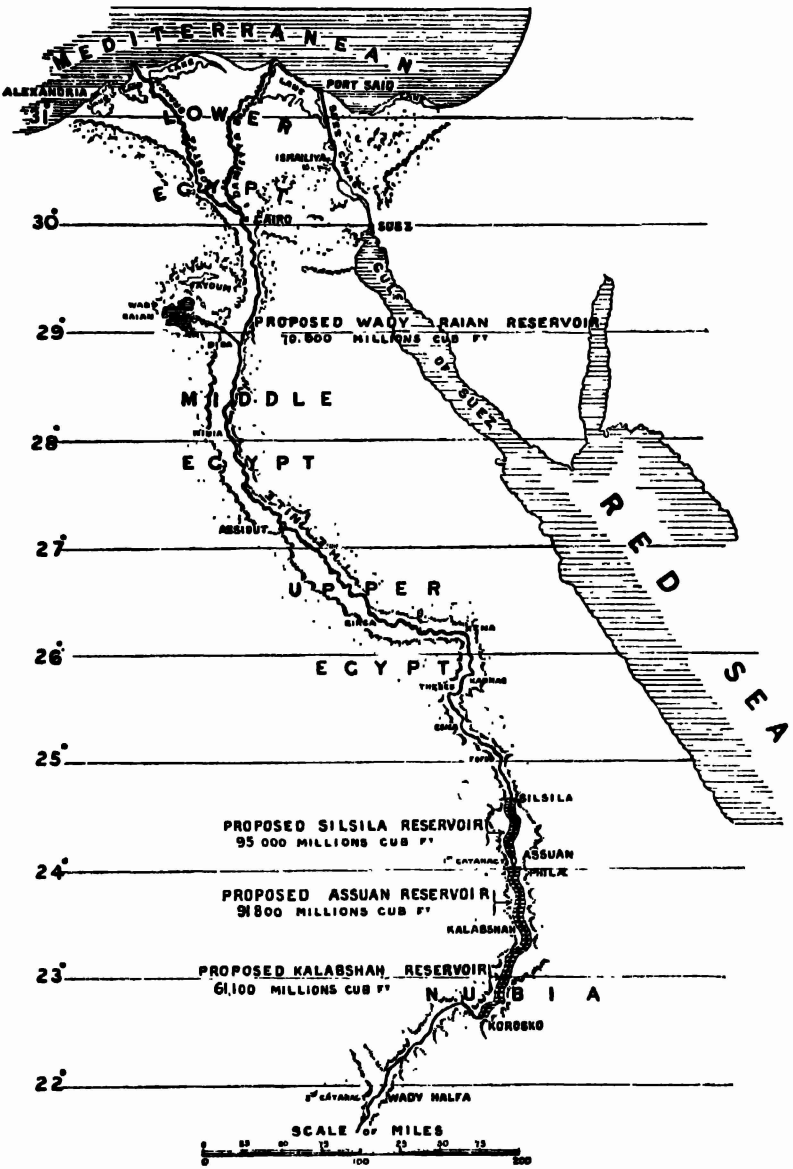
The first project on the list was originally proposed by Mr. Cope Whitehouse, who discovered in 1886 a great depression, called the Wady Raian, lying in the Libyan Desert, a little to the south of the Fayum in Middle Egypt. The lowest part of the bed of this depression is 131 feet (40 metres) below the bed of the sea, and 230 feet below the Nile flood level in its neighbourhood. It has an area of about 240 square miles at the level (27 metres above mean sea) to which it might be conveniently filled with water from the Nile.† The gross capacity of this depression below that level is 655,000 millions of cubic feet, of which it is calculated that 70,600 millions would be available, the remainder lying below the level at which the surface water could be efficiently drawn off into the Nile for the summer irrigation of crops in Lower Egypt. The depression is separated from the Nile by the desert hills which form the boundary of the Nile Valley, and by the width of the valley itself, which is about 15 miles. The nearest point of the depression is about 20 miles, as the crow flies, from the Nile. The land is entirely waste and uninhabited, so no injury would be done either to crops, houses, or people by its conversion into a lake. The proposal is to connect the Wady Raian depression with the Nile by a channel (for which several alternative routes are proposed) which will fill it to a certain level during the time when water can be drawn from the river without injuriously affecting the supply of the canals, and then, in the summer months, to draw off about 12 or 15 feet from the surface of the lake, either by the same channel, or by a different one joining the Nile at a point lower down its course, for the irrigation of summer crops in the Delta. One of the great advantages claimed for this project is that, if the supply channel is made sufficiently large, the lake would act as a vast compensation reservoir to the Nile floods; for the volume which it could accommodate would appreciably lower the level of dangerously high floods in the river. It is, however, questionable ‡ whether the Wady Raian could be made an efficient regulator of excessive Nile floods, at the same time as it served as a reservoir for summer irrigation; if it were to be an efficient regulator the level of the water in it would have to be kept low

* 'Nile Reservoirs.' Reports by Sir Colin Scott Moncrieff, K.C.M.G., Lt.-Col. Justin C. Ross, C.M.G., and Mr. W. Willcocks, M.I.C.E. Cairo, 1891.

† 'Memorandum on the Wady Raian,' by Col. T. H. Western, R.E. Cairo, 1888.

‡ 'The Fayûm and Lake Mœris,' by Major R. H. Brown, R.E., page 106.

in order to provide accommodation for an excessive flood, and, if it were so kept, it might not be possible to impound in it the water required for irrigation. The depression is so vast that it would take a



PROPOSED RESERVOIRS IN EGYPT.

long time to fill up to the level at which it becomes effective, and consequently, the money expended on the supply channel would be

lying, unproductively, at interest during that time. This fact materially increases the cost of the project as compared with the others, which would be effective as soon as they were completed. To fill the lake from the bottom up to the full level would require a discharge of 25,000 cubic feet a second running for 100 days each year for three years, without any allowance for evaporation and absorption; and Colonel Western estimated that it would take six years to fill the depression up to the lowest effective level when due consideration was given to the effects of evaporation and absorption, to the levels of the Nile flood, and to the volume which might be withdrawn from the river without injury to other interests. Even if the period of filling could be reduced to half this time, which is perhaps possible, the interest charge, which is not included in the estimates on page 88, would still remain an important factor in the cost.

The three other projects are alternative ones for reservoirs to be constructed in the Nile Valley itself. Above the first cataract at Assuan the longitudinal slope of the Nile averages about 1 in 12,500, so that a dam 60 feet in height would impound a lake about 140 miles in length. The sides of the lake would be the desert cliffs defining the valley of the Nile in which the river runs. These cliffs in many places are actually on the river bank, and at others they recede from it, leaving, as in Middle Egypt, land which is cultivated by the aid of irrigation from the Nile. In each of the three projects this culturable land would be submerged and the population would be displaced; but it is urged that cultivation of maize could be advantageously effected, on the land lying between the high and low water level of the reservoir, during the time—June to November—when the water would be low. In each case it is proposed to impound water by the construction of a granite dam from 70 to 80 feet high across the Nile. The dam would be pierced by flood openings of sufficient capacity to discharge the entire maximum flood of the Nile, some 420,000 cubic feet a second, with a velocity of about 20 feet a second. It is necessary to pass the flood waters through the reservoir, as is done in the case of the Bhatgarh dam,* at a low level, in order to prevent the vast deposits of silt which would undoubtedly accumulate if the dam were made solid and the flood waters were passed either over it or by escapes to the side of it. It is proposed that the flood openings shall be closed, and the water impounded, after the heavy silt-bearing floods of August and September have passed through the dam: but the actual time of the commencement of regulation at the

* See pages 79 and 177.

dam will depend to some extent on the effect produced on the navigation of the river by the restriction of the discharge.

The Assuan reservoir project, which is due to Mr. Willcocks,* consists of a dam placed across the Nile just above the first cataract at Assuan and just below the famous ruins on the island of Philæ, which would be submerged when the reservoir was full. The bed of the river is granite, and the site offers, in other ways, great advantages. The Kalabshah project lies above the Assuan one, and is practically the same except that the dam is 33 miles higher up the river, and the volume of water impounded is consequently less: the site, too, is less favourable for the construction of the dam, and the granite rock is not as hard as that at Assuan. In both these cases the impounded water would stand back to Korosko. At Silsila, which was a site originally selected by Baron de la Motte for a reservoir, the dam would rest on sandstone at a point where the river passes through a gorge 950 feet in width. This site would give the largest reservoir, and it would have the advantage of being lower down the Nile, so that less water would be lost in transit down the river to the canals; but the fact that the foundation would be on sandstone instead of granite, and that the sandstone† is not very good in itself, is a disadvantage. The impounded water would extend back to Assuan, and would submerge the present town. Any one of these projects would be effective as soon as it was completed, and would have the advantage over the Wady Raian project in that respect, but it would not, as the Raian reservoir might, be any aid in the regulation of excessive floods in the river.

The competition between these rival projects is one which will demand close scrutiny on the part of those who have to decide upon them: there are many arguments for and against each of them which require very careful study. The vastness of the projects as compared with anything of the kind which has as yet been carried out renders them of interest to engineers of all countries.

* Reports quoted in footnote, page 89

† Mr. Willcocks' report, quoted in footnote, page 89.

CHAPTER VI.

PERENNIAL CANALS IN DELTAIC TRACTS—EMBANKMENTS.

Formation of Deltas—The Mahanuddee Delta in Orissa—Decrease in Waterway in Deltaic Streams—Embankments necessary in Deltaic Projects—Limits to Embankments in Deltas—Increase in Flood-levels due to Embankments—Deltaic Tracts at Confluence of Rivers—Reduction in the Waterway of the Sone River as it approaches the Ganges—The Floods of the Gunduk—Drainage essential in Deltaic Projects—Embankments in Deltaic Tracts—Damage due to Embankments—Effect of Embankments in increasing or decreasing Discharge—Disadvantages of Embankments.

THE canals of India which are drawn from rivers having a perennial supply of water may be broadly divided into two classes. First, canals which lie in the deltas of the rivers from which they draw their supply, and secondly, canals which are drawn off from the upper portions of rivers before they assume a deltaic character. The canals of the first class are chiefly those of Madras and one or two in Bengal, while nearly all the canals of Upper India fall in the second class.

The delta of a river is usually spoken of as the tract of land, near the junction of the river with the sea, where it divides into two or more branches; but it would be better to define the delta as the land which has been formed, or of which the level has been distinctly raised, by the inundations of the river. The slope of nearly all rivers decreases from their source to the sea: the general section of a river is that given in Fig. 1, Plate XXV. In the hills the river is a torrent; at its exit from the hills it may have, as the Ravi, the Ganges, and the Jumna do have, a slope of from 10 to 15 feet a mile; in the plains this slope is reduced little by little, until, near the sea, the slope may be as little as 3 or 4 inches a mile, as it is in the delta of the Ganges. The velocity of the streams in the higher parts, where the slope is steepest, is often too great for the soil, and the rivers cut into it, forming the *Khadir* and *Bhangar* lands which have been already described (page 9). In the lower reaches the velocity is greatly reduced and the river deposits the material, which it holds in suspension, in its bed, which is gradually

raised by the process. The channel soon becomes too small for the flood discharge and the water spills over the banks which are raised by the silt deposit. In some cases such as the Godaveri in Madras or the Mahanuddee in Orissa, there are indications that the sea, in prehistoric ages, extended to the hills which stand near the heads of the delta of these rivers, and that the land which now lies between the hills and the sea, has been entirely thrown up by them. Plate XXV. shows the general features of the delta of the Mahanuddee, which has an area of about 2000 square miles between the Beropa and the Khoakye branches. The general level of the ground at the head of the delta at Cuttack is about 70 to 75 feet above the sea, and there is a fairly uniform slope in the land surface from that point to the sea. A great flood in this river has an average surface slope of about 0·25 per 1000 in the delta. The great floods of this river attain to more than 1,500,000 cubic feet a second, and the amount of solid matter which is annually brought down must be very great (see page 37).* As soon as the river comes in contact with the ocean the waters spread out, more or less in a fan-like shape, and deposit the mud which they carry, until land is formed, which gradually rises above the sea-level. Every succeeding flood spills over the low ground and raises it still further, depositing the greater portion of its silt near the channel of the river; so the land, as it is raised, rises more quickly near the banks, and more slowly, the further the silt-laden water has to flow from the main current. The channel of the river is subjected to floods varying greatly in volume, and after a long series of low floods, which tend to restrict the waterway of the river, one of exceptional volume occurs, which washing over the newly formed soil cuts a fresh channel, or it may be two or three fresh channels, radiating from the point where the delta commences. These new channels become more or less permanent, and in their turn throw out silt into the sea, and form smaller deltas of their own, which amalgamate with and extend the dimensions of the fan-like submarine mound, which is continually being pushed out, as it were, into the sea. Hence it occurs that the branches, into which a river divides itself in its delta, are all more or less on higher ground, and that a section of a delta (see Plate XXV.) shows the channels on the ridges, the hollows between the ridges being sometimes found to be actually lower than the beds of the channels near them. The branches occasionally burst through their banks, and force new channels in the lower ground, which, in its turn,

* 'Report on the Floods of the Mahanuddee River,' by R. H. Rhind, Esq., Bengal Secretariat Press.

becomes raised by the silt deposits of the new channel. As the delta advances, the slope of the bed and surface of the river must become gradually less and less, for the length of the river increases and the level of the sea is constant.

A river, running in the soft soil of a delta, easily changes its course; the actual channels, as defined by the levels of the margin of their banks, are, from the nature of the method by which they are formed, not capable of carrying extreme floods, and the steady advance of the delta is always making them less competent to do so by reason of the continual decrease in slope. Consequently the relative dimensions of the main channel and branches are sometimes greatly altered. An alteration of this kind has been approximately gauged in the case of the Mahanuddee river. That river was subjected to extremely high floods in 1834, in 1855, and in 1872, and it has been calculated that, during the period which elapsed between the floods of 1855 and 1872, the carrying capacity of the Mahanuddee branch * had deteriorated to the extent of nearly 80,000 cubic feet or ten per cent. of its ordinary volume. So the relative importance of any branch is always liable to alteration in any great flood. Plate XXV. shows the approximate discharges, in the great flood of 1872, of the various channels, into which the delta of the Mahanuddee river is divided. The total discharge of the river above the delta was 1,503,627 † cubic feet per second.

This volume is the entire flood which had to be ultimately carried to the sea, but it did not find its way to the sea entirely through the channels of the river: from 30 to 40 per cent. of the water was spilt over the banks of those channels, and ultimately passed to the sea through the low ground which lies between them. It was found that the total loss of discharge experienced by each principal branch of the river during the flood was as follows:—

	Loss in cubic feet a second.	Percentage of Loss on Original Discharge.
Beropa Branch ..	33,943	30·1
Katjori „ ..	174,985	39·1
Mahanuddee „ ..	232,897	35·9

* Memorandum by R. H. Rhind, Esq., being No. 15 of 'Papers relating to the Orissa Canals,' Bengal Secretariat Press, 1884.

† 'Report on the Floods of the Mahanuddee River during the year 1872,' by R. H. Rhind, Esq., Bengal Secretariat Press, 1875.

It is a common feature of deltaic rivers that the areas of the cross sections of the various branches diminish as they approach the sea. This is remarkably the case in the branches of the Mahanuddee, and the fact finds expression in the figures on the diagram (Plate XXV.): it will be noticed that the discharge at the head of any particular reach of the river is always considerably more than the united discharges at the heads of the branches taking off at the lower end of the reach, showing that the waterway is insufficient to carry the entire discharge: this point is one of considerable importance.

The delta of a river offers great advantages for irrigation: the soil is usually rich alluvium, the slope of the country from the head of the delta to the sea is always uniform and gentle: the slope transversely is also fairly uniform from the banks of the various branches to the natural drainages which lie between them: these drainages offer convenient means, when graded channels are opened through them, for discharging the surplus water: the fact that the river channels are on the ridges gives a comparatively easy command of the country. By throwing a weir across the head of the delta, and running canals along the margins of the branches, the whole delta can be irrigated. It is, however, necessary to construct a series of marginal embankments in connection with any delta scheme, for, as, in the nature of the case, the whole area under command of the canals is more or less subject to inundation, it is necessary to confine the floods to the river channels, or the crops in the low ground might be destroyed or damage might be done to the canals. To a considerable extent the canals would themselves form the marginal embankments, as they usually run on or near the banks of the rivers; but this would not always be the case. In designing a scheme of canals in a delta, with a connective system of protective embankments, consideration has to be given to the tendency of the river to change the allotment of its floods between the different branches, and it is usually, if not always, necessary to carefully regulate the discharge of the branches by weirs across both the main channel of the river and the branches also; the fact also of the reduction in the cross section of the branches as they approach the sea is of great importance in the design of the embankments, for a material increase in the flood-level will be obtained if the discharge of any channel is not only confined within it in its higher portions, where the usual spill over the banks may be considerable, but is further confined to the lower portions where the slope is reduced, and where the channel is also so reduced as to be incapable of carrying,

between its banks, the discharge which the upper portions can bring down to it.

The necessity for the regulation of the discharge of the branches of a deltaic river is exemplified by the case of the Mahanuddee (Plate XXV.). It had been found that the head of the Katjori branch,* which takes off immediately below a gorge in the main river, was enlarging greatly after each year's floods, and that the increased volume, which was being drawn into it, was far greater than the channel could possibly carry. The result was that there were extensive floods from the lower reaches of the branch and destruction of crops; the embankments also which had been constructed to protect the country were unable to resist the increased pressure brought on them by the heightening of the flood-level due to the increased discharge. At the same time the head of the main, or Mahanuddee branch was found to be silting up, and that it was not carrying the proportion of the entire volume of the river which its general capacity enabled it to carry off. It was consequently decided to regulate the discharge of the Katjori by a stone spur which was constructed across the head of that branch in a direction diagonal to the course of the stream, and which ended in the high sand ridge which divides the channels of the Mahanuddee and the Katjori. This spur, which was of dry rubble roughly packed, was completed in 1860, but it proved insufficient, and it was ultimately replaced by a masonry weir built across the stream of the Katjori, and strongly supported by an abutment on the Mahanuddee side, and a dividing embankment heavily revetted with stone. This weir has completely checked the enlargement of the Katjori and entirely separated the waters of the two branches. A similar instance of the necessity of controlling the branches of a deltaic river is found in the delta of the Cauvery, which commences near the island of Srirungum, Plates V., p. 14, and XLI., p. 142. The main river divides at that point into two branches, the Cauvery and the Coleroon. The latter has a larger volume, a more direct channel, and more rapid slope, and the tendency was for the Cauvery to silt up, and for the whole stream of the river to pass down the Coleroon. This tendency was perhaps increased by the fact that the Cauvery, near the lower extremity of the island of Srirungum, was partially obstructed by the Grand Anicut, a work constructed by the natives to assist the irrigation of the delta.

The first improvement effected was the construction of a weir or anicut across the Cauvery and Coleroon at the upper end of the island to

* "A Short Sketch of the Scheme of Works proposed . . . in Orissa," by A. G. Crommelin, Esq., 'Papers relating to the Orissa Canal,' 1884.

regulate the discharge of the river between the two branches. Both in this case and in that of the Mahanuddee the construction of these regulating works was essential before it was possible to carry out the irrigation works, and to decide on the heights to which embankments had to be made to provide for confining the discharge of each branch within the limits of its own channel.

On the matter of embankments it has to be borne in mind that there may be a limit to which it is expedient, or even possible within any reasonable cost, to embank the branches of a river in its delta. The spill over the banks of the branches, and the diminution in the capacity of the branches as they approach the sea, may be so great that the height of the necessary marginal embankments becomes prohibitive. In order to determine how far embankments can be carried, and what the height of them should be in any particular case, it is necessary to survey all the branches, to cross-section them at frequent intervals, to record the actual levels in high floods, to record the varying surface slopes, and to calculate from these data the discharges at all the important points. It is further necessary to determine the probable maximum flood which may occur (for it is rarely that such a flood will occur during the investigation) and to estimate how this flood will be divided among the branches, either by nature or by the works which it will probably be found necessary to erect to apportion the total volume, in the most practicable way, according to the relative capacities of the branches. Then, having fixed the allotment of each branch, the discharge has to be followed down the channel and its ramifications; the discharge, in any reach, being divided proportionately between the two (or more) channels which may flow from it: in this way the whole discharge of the river will be marked out on a rough chart in the manner shown in Plate XXV. It is then necessary to ascertain the surface-level of the water which it will be necessary to have in each channel in order that it may be capable of carrying the discharge allotted to it in the chart. This has to be done more or less by a system of trial and error, assuming, in the first instance, surface slopes about the same as those which originally existed. The process is extremely laborious, but the engineer will soon convince himself that it is absolutely necessary before any system of canals and embankments can be laid down in a delta with a reasonable prospect of security, for he will soon find that the discharges which he is theoretically heaping on to the channels, which become more and more restricted as the quantity increases, will raise the water surface to a dangerous extent, and he will be compelled to either open up

entirely new channels or to abandon his embankments, on certain tracts, and allow the flood access to the lower ground which lies between the branches.

It will generally be found, too, in an extensive delta, that, just as regulating weirs were found necessary at the head of the delta to distribute the discharge, so they will be found necessary lower down to divide it to the best advantage among the smaller ramifications.

A survey and investigation of this nature has been made of the river Mahanuddee * and its delta; this showed, as has already been stated, that the joint capacity of the various channels forming the outlets of each branch was only equal to 60 to 70 per cent. of the capacity of the head of the branch, and that the volume of water which spilt over the banks of the channels at various points aggregated about 600,000 cubic feet a second, and that 1000 † square miles of country were inundated. A scheme was worked out on the following basis:—

Branch.	Discharge at the Head of each Branch in Flood of 1872, in cubic feet per second.	Proposed Discharge to provide for Maximum Flood.
Barung river and spills above Cuttack	132,547	Nil
Mahanuddee branch	609,213	954,000
Beropa „	112,662	112,000
Koakye „	201,936	45,000
Katjori „	447,279	460,000
Total	1,503,637	1,571,000

It was proposed to reduce the discharge of the Koakye branch on account of the damage done by its floods, and a corresponding increase was allowed in the main Mahanuddee branch as its capacity was sufficient. It was shown that, if a comprehensive system of embankments were constructed to pass these quantities, without spill, the flood-level would be raised approximately as follows in the upper reaches of the branches:—

* 'Report on the Floods of the Mahanuddee River,' by R. H. Rhind, Esq. Bengal Secretariat Press, 1875.

† 'Papers relating to the Orissa Canals,' page 50. Bengal Secretariat Press, 1884.

Branches.	Number of Feet by which the Surface-level of the Flood would be raised above that of the Flood of 1872.	
	From	To
Mahanuddee Branch—		
From weir to head of Sook Pyka	3·79	5·87
„ head of Sook Pyka to Cheerturtollah ..	5·25	..
„ head of Cheerturtollah to outfall of Pyka..	3·68	6·60
Beropa Branch—		
First reach	0·00	5·87
Koakye Branch	reduced	
Katjori Branch—		
From Cuttack to head of Soorooah	0·41	0·46
„ head of Soorooah to outfall of same ..	1·21	4·48
„ outfall of Soorooah to head of Daib ..	2·95	3·17
„ head of Daib to head of Belloakye	2·52	5·16

The resulting velocities varied from 3·23 to 4·19 feet per second. The calculations were carried further forward into the smaller branches, and it was found that the flood-levels would increase to prohibitive heights in certain places. It was consequently proposed to leave certain tracts, aggregating some 200 square miles in area, unprotected, and to let them be open to inundation from the river, so as to decrease the volume thrown upon the lower channels of the branches. A concrete example of this kind shows the necessity of care in dealing with delta projects: an increased flood-level of 5 feet is a serious matter in the case of a breach in an embankment. The damage done by a breach in an embanked river is far greater, in the area immediately affected by the breach, than that which occurs from the spills which would ordinarily flow over the country at the same place if the river were not embanked.

Any system of embankments, it must not be forgotten, is subject to the disadvantage that it stops the deposit of the silt which the floods carry over the flooded area and leave upon it, and it thus interferes with the action of nature which gradually raises the level of the land by many successive deposits, each of inappreciable amount.

The action which goes on at the junction of a silt-laden river with the sea occurs also, more or less, at the confluence of two rivers. Fig. IV., Plate XXV., shows the confluence of the Sone river, the Gogra river, and the Gunduk river with the Ganges; and Fig. V. shows, in

section, the confluence of the Sone and Ganges. In each of these instances the tract of country shown in the plan is deltaic in character, that is to say, the main channels of the three tributaries are, more or less, on raised ground, and the various spill channels on the east of the Sone, and the Nuddees, as they are called, on the west of the Gunduk, are on slight ridges of the country, between which there are drainages which receive and carry off the rainfall. But the deltas of these rivers are not subject now to annual inundations, as the deltas of rivers on the sea coast are in a greater or smaller degree. It is only on occasions of extreme floods that inundations of any importance occur, and in the case of the Gunduk these have been largely reduced by embankments on the river.

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There are reasons for supposing that the present channel of the Sone near its junction with the Ganges is, geologically speaking, a comparatively modern one, and that the course of it, at one time, was to the east of the present city of Patna. This supposition is supported by the fact that the country on the east of the present course of the river is intersected by spill channels which may have been old courses of the river, but the country on the west side has no spill channels which have the deltaic character of those on the east. The course of the river has, in all probability, been gradually pushing its way further west, as it has gradually raised its bed and banks by the deposit of the sand and silt which is continually being swept along its bed or carried in suspension in its water.

The Sone river in flood has a surface slope of rather more than 2 feet a mile (·40 per 1000), but the Ganges slope is only about 5 inches a mile (0·08 per 1000); the slope of the Gunduk is about 9 inches a mile. A great flood occurred in the Sone in July 1876 which flooded the delta disastrously: it breached both the Patna Canal and the Arrah Canal in places, and inundated the tract cross-lined in blue in the plan. On the east side the flood first filled and then overflowed the banks of the spill channels into the low ground between them. This flood was carefully investigated, and it was found that the maximum discharge was 830,000 cubic feet a second above the various points of spill, but that at the bridge which carries the East Indian Railway over the river the maximum discharge was about 560,000 cubic feet only, so that the volume of spill from the river into the delta at the top of the flood was 270,000 cubic feet a second. The reduction in the discharging capacity of the Sone river after it enters its delta is very similar to the reduction in the case of the Mahanuddee: that is to say, the river channel in the

case of the Sone and the various channels in the case of the Mahanuddee are not able to carry more than about two-thirds of a maximum flood. The Patna Canal on the east bank and the Arrah Canal on the west both embank the Sone river to a certain extent, and, since the flood of 1876, certain distributaries have been added on the east side which have reduced the flooded area on that bank. The question of fully embanking the river on both banks, so as to exclude the floods entirely from the inundated tract, was considered, and, if it had been done, the area under command of the canals might have been increased, but it was found that the increase in flood-level would have been about 5 feet in the lower reaches of the river, and it was rightly considered inexpedient to raise the flood to this extent. The spill from the Sone river is about five times as great on the west bank as it is on the east bank: this fact seems to support the opinion that the river is gradually working to the west.

The deltaic tract on the east of the Sone river is irrigated from the Patna Canal by a series of distributaries which are aligned on the banks of the old spill channels.

The Gunduk river used to spill largely over both its banks: the spills on the west side have been entirely prevented by a line of embankment which extends continuously from the mouth of the river up to a point above the heads of the four "nuddees," or spill channels of a deltaic character, which traverse the country. On the east side an embankment has also been constructed, but it is not continuous: an opening is left at the head of the Byar Nullah through which a large volume passes in floods, and there are other large openings in the embankments which afford considerable relief to the river at these times. The embankments are frequently pierced by sluices through which water is at times drawn from the river when in flood, for the irrigation of rice crops in the low ground. On the western side of the river the Sarun Canal has been excavated by which a certain amount of water is supplied into the four "nuddees" during all times of the year; as these channels are on slight ridges the water can be drawn out on to the lower ground by cuts through the banks of the streams. There is unfortunately very little information available as to the discharge and volume of spill from the Gunduk, but the deltaic character of the country on the west bank is clear and the utilisation of the old spill channels as canals for supplying water for irrigation is interesting. The Gogra river also spills largely in years of very high floods over both its banks near its confluence with the Ganges. It is very probable that in both the Gogra and the Gunduk the waterway of the channels decreases as they

approach the Ganges, but this has not been proved to be the case as it has been in the case of the Sone.

The chief crop grown on all deltaic tracts in India is rice. This crop requires a large volume of water and it benefits by a constant change of water, so that the cultivators, when they get the opportunity, will drain and refill the fields as much as they can. This is one reason why drainage works are more necessary in connection with deltaic irrigation systems than in others. The alignment of these drains is generally simple, as there are usually well-marked hollows between the ridges in which the drainage cuts are properly placed, but it is sometimes difficult to find an efficient outfall which will not silt up by the tidal action to which it is probably exposed.

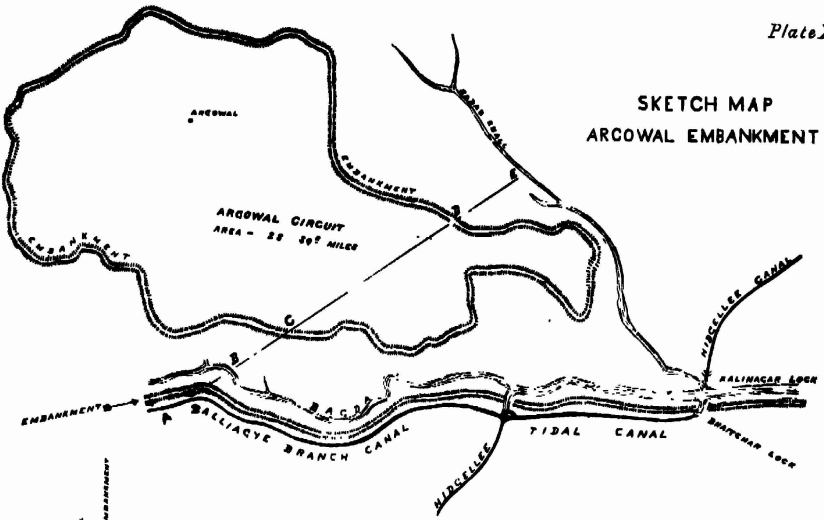
In the previous pages the necessity for embanking the margins of the natural channels in deltaic tracts, before any effective system of irrigation can be developed, has been pointed out. Such embankments, however, although essential, are by no means without disadvantages, which in some cases are of considerable magnitude. Any deltaic tract is, more or less, in course of formation: the land in it has been the result of the deposits of untold ages, and the fact that embankments are necessary to protect the land from floods, is a proof that it is still being raised by the action of the river. By embanking the channels and thus depriving the land of the yearly deposit its growth is stopped. In the higher portions of a delta this is perhaps of little importance, but there are cases, more particularly where the lands are within tidal influence, in which the result of embankments is disastrous. The immediate result of an embankment on the margin of a river or tidal channel which carries water laden with silt, is, that the land lying between the embankment and the stream—which is often of considerable width—is raised by the annual deposit more quickly than it would otherwise be, while the land within the embankment is not raised at all. In some cases, especially within tidal influence, the beds of the channels are raised simultaneously with the banks. The process is often extremely slow and inappreciable, but in other cases this is not so. The result is that the embankments have to be raised from time to time to resist the increased flood-level of the stream, and the dangers due to a breach of them become aggravated. The land lying in the protected area is drained, when the embankments are first made, with comparative ease, through the local drainages which are provided with sluices into the main channel; but as the banks and bed of this channel are raised the drainage of the lands becomes more and more difficult and expensive,

and in some cases in the Midnapore district of Bengal, it is recognised that the only possible way of draining certain embanked tracts in which this action has been going on, would be by dredging the deposits from the streams. The following description of a case of this kind is taken almost verbatim from a note by Col. J. M. M'Neile, R.E.,* on Bengal embankments.

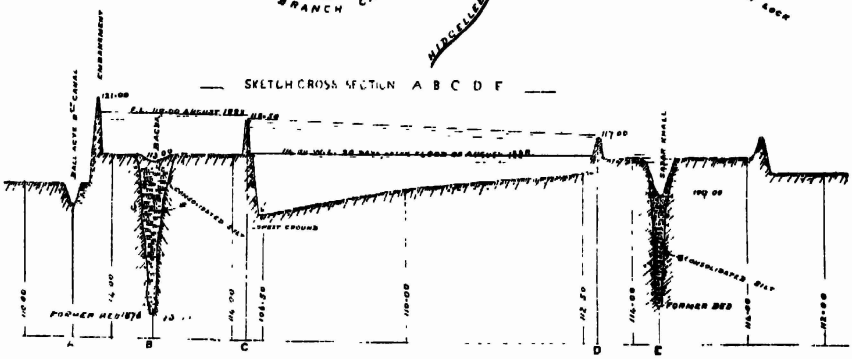
Plate XXVI. shows, in the small map, the general arrangement of the embankments in the Contai district of Midnapore, and the plan on a larger scale shows the Argowal Circuit embankment, which encloses in a ring fence about 28 square miles of country, which was formerly subject to frequent inundation from the Bagda and Sadur rivers. A section is given, taken right across this tract of land, which shows the reduced levels of the ground, the embankment crests and the flood of 1888, which was a very destructive one. The Bagda and Sadur channels are within tidal influence, and the waters are at times heavily charged with silt. The embankment, although it is known to have existed in the time of the East India Company, is probably of no great age, as the silting up of the land on the river side of the embankment has been very rapid in late years. This land is now from 2½ to 7 feet above that lying within the protected area, which is probably about the same level as it was when the embankment was first made. The object of the embankment, which was probably from 4 to 6 feet in height only, was to reclaim a salt-water swamp, and the drainage of the enclosed area was at first easily provided for by sluices, the land on both sides being at the same level. The action of this embankment in connection with those on the other side of the Bagda and Sadur rivers, has been to confine the tidal deposit (which formerly must have taken place over all the low country) to the area outside the embankment, raising it (and probably the high tide level also to a certain extent) so that in heavy rains the flood waters from inland have to pass over a narrowed area with a smaller slope and the discharge of the floods is impeded. The result was that in 1888, when heavy floods occurred, the embankment, although it had been previously raised, was unable to resist them. The water topped and breached it, swamping the whole of the area enclosed by the embankment and completely destroying the crops of that year. The people and cattle were forced to take refuge on the unbreached portions of the bank. The cross sections in the plate show clearly how the rivers have deteriorated and how the land between the embankments and the river has risen in this case.

* Lately Chief Engineer of Bengal. The report is dated the 24th May, 1890.

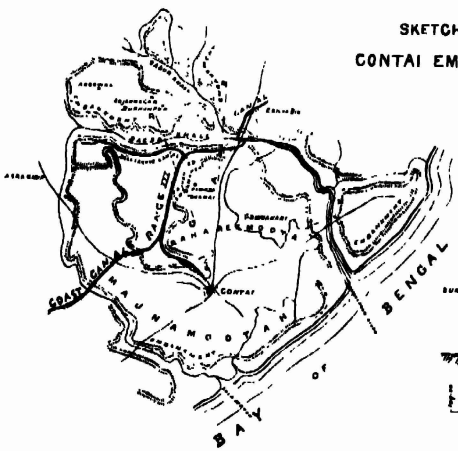
SKETCH MAP
ARCOWAL EMBANKMENT



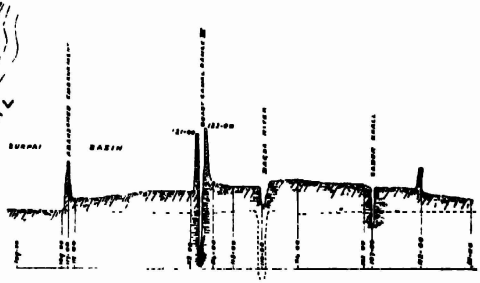
SKETCH CROSS SECTION A B C D E



SKETCH PLAN
CONTAI EMBANKMENTS



SECTION ON LINE A.B.



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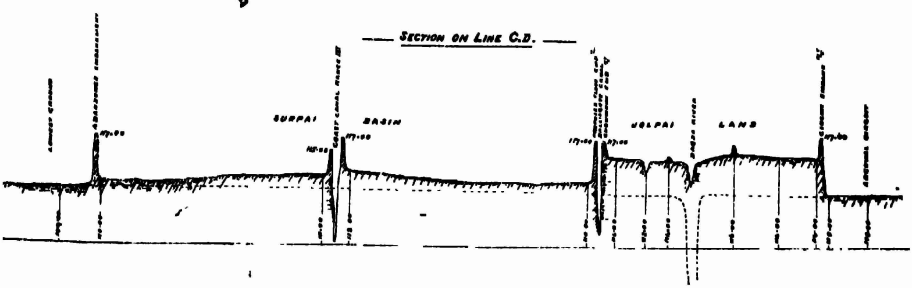


Embankments which are constructed to protect low-lying lands from inundation have the effect of decreasing the maximum discharge of the neighbouring channels if they are purely or mainly tidal estuaries (or *khalls*), and they have the effect of increasing the maximum discharge of rivers which lie above the action of the tides. An embankment confines to the river that portion of the water which would otherwise flow over the land; hence, when the water is coming entirely from above (as in the case of a river above tidal flow) the discharge, at and below the site of the embankment, is increased, as the water, which might have been distributed over the land, is compelled to pass forward at once. But the case is different in a purely tidal channel which receives little or no drainage water from above: in that case the embankment reduces the amount of water which flows up the channel at flood tide by the quantity which would have spilt over the country had there been no embankment, and, consequently, at ebb tide, the receding flow is also reduced. In these cases the low-lying land is a reservoir which receives and discharges, more or less, at each tide a definite volume of water: when the land is reclaimed by an embankment this action ceases and the flow in the tidal channel is reduced. When this reduction of discharge occurs the tidal channel very rapidly accommodates itself to the circumstances and silt is deposited in large quantities. In deltaic tracts there are channels which are purely tidal and receive little or no drainage water from above: there are others, which, lying within tidal limits, flow during a great portion of the year almost entirely by tidal influence, but, in the rainy season, are called upon to discharge large volumes brought upon them by drainage from the plains above. It is in these channels especially that embankments are works which produce unexpected results: the discharge of drainage varies greatly in different years and there are often long periods of years, during which the discharge may be moderate: during these years the tidal outlets of a large river, when the low grounds are embanked and the purely tidal flow is checked, deteriorate in capacity, and when a year of heavy floods occurs the reduced channels are overloaded and extensive breaches are inevitable.

Independently altogether of the injury which embankments may effect, by impeding the natural accretion to the soil which inundation produces and by causing the deterioration of channels, there is the fact that the protection of a tract from inundation is not in itself an unmixed blessing: inundations from silt-bearing rivers, although they may and often do injure the standing rice crop, are at the same time very advantageous to the lands from the manure they leave behind them

which improves the cold weather crops greatly. It is not an unusual event to find lands on the river side of an embankment, and which are therefore subject to inundation, realising higher rents than the protected lands within the embankment. The rich deposits in the first case more than compensate for the risk of damage to which the crop is liable.

In the upper reaches of most rivers and particularly in Bengal there are tracts of land which are subject at intervals of ten or fifteen years to extensive inundation due to unusual floods brought down by the rivers above them. These tracts act as compensation reservoirs for these unusual floods, impounding the surplus waters for a time until the river channels below can find leisure to carry off the surplus. Many of these tracts are slightly embanked and agitation for the complete protection of them is periodically made after unusual inundations. Those who are interested in the entire protection of these areas fail to realise that the embankment of each tract increases the difficulty of protecting the one below it and that when embankments are commenced in the upper reaches of a river and the surplus waters are compelled to flow forward, it is essential, if equal protection is to be given to all, to carry the line of embankment unbroken to the sea. It is now beginning to be realised by some engineers and officials in Bengal that embankments on the margin of silt-bearing rivers in deltaic or quasi-deltaic tracts may be a source of difficulty and even of danger:* on the Damooda river, and on the Goomtee, lengths of 20 and 10 miles of embankment respectively, which were originally constructed to prevent the spills of the rivers, have been deliberately abandoned in order to relieve the congested channels of the rivers. In several other cases also proposals are being made to remove embankments which, as in the case of the Argowal Circuit embankment, are known to be dangerous to the lives of the residents in the "protected" area.

In this matter the experience of Egypt is valuable. The floods of the Nile are reduced by the action of the "basins" (page 24) which form compensation reservoirs for the floods, but, nevertheless, the marginal embankments of the river extend practically from Upper Egypt to the sea. If the system of flooding the "basins" were discontinued, the embankments would be insufficient to afford protection in the lower reaches of the river.

* Note quoted above.

CHAPTER VII.

GENERAL NATURE OF HEAD-WORKS.

Purposes of Head-works—Influence which Silt has with reference to Site and Design—Oblique Weirs and those at right angles to the Axis of the Stream—Head-works in Deltaic Tracts—Old Weirs—The Grand Anicut in Madras—Classes of Indian Weirs—Dangers to River Weirs—Onward Flow of the Materials forming the Bed of a River—Increase of Level of River Beds above Weirs—Sluices inefficient to check Deposits above Weirs—Currents induced by Accretions in a River Bed above a Weir—Parallel Currents along the Face of Diagonal Weirs—Retrogression of Levels.

ONE of the most important matters to be settled in connection with any irrigation project is the proper site and the nature of the head-works. These include the weir across the river, the under-sluices in the weir, the head-sluices of the canal, and, if the canal is to be navigable, the head-lock from the river to the canal. It is not, in all cases, necessary to construct a permanent weir, as it may be possible to divert the water from the river to the canal by means of temporary spurs constructed right across it when the river is very low, or thrown out for some distance into it when it is not necessary or possible to draw off the entire discharge. But this method is generally only practicable when the river is a shallow one and the banks low, as otherwise the canal would have to be in very deep cutting; and it can only be employed where the bed of the stream is narrow and either in boulders or rock; in broad rivers with sandy beds the annual cost of the spurs would be very great and it would be impossible to construct them in time to ensure a constant supply. The main objects of a weir are to raise the level of the water in the dry season, when the river is low, and to provide a means of forcing it through the head-sluices of the canal: the under-sluices, which are openings in the weir itself, are necessary to create a scour, during the flood season, to keep a definite channel open above the weir in the neighbourhood of the canal head, so that there may be no difficulty in leading the water to the head-sluices when the river is low.

The selection of the site of the head-works is often a matter of con-

siderable difficulty. The problem is generally to find the best site for a weir on a given river in order to command as large an area as possible, but it may be to select a site for a weir to command a particular tract of country. In either case one of the most essential points to be first considered is the nature of the silt carried by the river: whether it is fertilising or the reverse: what proportion of it it is desirable to carry down the canal, and whether the soil, in which the canal is to be cut, can stand the velocity which will carry the silt. When the slope of the canal is determined an idea can be obtained, from the levels of the country, of the point where the water from any point of the river can be delivered on the surface of the ground, and the area under command of different sites can be ascertained. The approximate lengths and depths of cutting of the unprofitable portion of the canal, which lies between the head-works and the first point of irrigation, can also be roughly worked out and it is necessary to do this as the cost of this portion may often be very great. The height of the weir above the bed of the river should next be determined: this will depend on the depth of water in the canal and the level of the canal bed with reference to it; here again the important question of silt deposit must be borne in mind (see page 39): if it is feared that there will be much difficulty with silt it is desirable to keep the under-sluice floor as low as possible and the canal bed as high as possible, a combination which results in a high weir, and it has to be considered whether the cost of foundations may not be unduly enhanced if the under-sluice floor is depressed. Then the effect of weirs of various heights on the flood level of the river should be worked out: the flood discharge must be ascertained from gauge readings, from cross sections of the river and known surface slopes, and from these data the depth on the crest of the weir which will be necessary to discharge a maximum flood can be ascertained, and hence the afflux or height by which the flood will be increased by the weir. This point is of extreme importance, as upon it depends the necessity for constructing embankments to control the river above the weir: if the afflux is great the country above the weir may be inundated and there may be a danger of the flank of the work being turned by the river. In light sandy soils this might result in the river cutting out another course for itself and leaving the weir at a distance from the new channel of the river. This difficulty may be avoided by constructing a comparatively low weir and placing folding shutters on the entire length of the crest which can be raised in the dry season and depressed in the floods to allow of the free discharge of the flood waters. Another point which requires consideration in the selection

of the position and design of head-works is whether the weir should be placed at right angles to the course of the stream or inclined at an angle to it. In deltaic systems where the soil at the site of the weir is friable, and in all cases where the bed of the river is light sand, it is essential that the weir should be at right angles to the stream, for a skew weir would induce parallel currents which would scour in front of the weir and probably undermine it: but on rock, and in the boulder beds of rivers near the hills, a weir on the skew may frequently be constructed with the advantage that a better control over the cold weather channel is obtained, for the main current of the river is directed toward the under-sluices and a powerful "draw" is obtained which tends to keep the cold weather channel open. Weirs at an angle to the stream have been constructed on the Jumna river, at the head-works of the Western Jumna Canal (Plate XXXI.), and on the natural channel which forms the main feeder of the Eastern Jumna Canal, where the soil is largely composed of boulders. On the Bari Doab Canal, which takes off the Ravi river at a point where the slope is more than 20 feet a mile (see Plate XXX., page 124), the weir was built square across the river, and a great deal of difficulty has been encountered in maintaining a channel to the head-sluices of the canal. The bed of the river has filled up to the weir crest with boulders, and the cold weather channel is controlled with difficulty: this would probably have been avoided to a great extent if the weir had been at an angle to the course of the stream.

The most suitable position, as a rule, for a weir and head-works of a canal is on a portion of the river where the channel is straight, the velocity uniform, and the sectional area of the stream fairly constant. A narrow gorge of a river appears to have the advantage of cheapness, but it may be the most expensive on account of the greater velocity and greater depth of the water, which produce a stronger frictional action on the weir, and necessitate heavier materials or stronger work. A particularly wide reach of a river has, on the other hand, the disadvantage that, the average velocity being decreased, the deposit of silt and sand is encouraged, and the bed of the river above the weir is likely to become so raised that it may be difficult to keep a channel open to the head-sluice of the canal. The nature of the soil on either side of the weir for some miles above it has to be examined: it is important to choose a site where the river shows no signs of changing its course, or expensive training works may be required. Another point of importance is to select a site as near as possible to a supply of stone for constructing the

weir if there be any in the neighbourhood: the lead of building materials is an important factor in the cost.

In the case of irrigation projects in deltaic tracts there is usually but little option in the selection of a site for the head-works: if the areas lying between the various branches are to be irrigated, the weir must necessarily be at the point where the branches leave the main stream.

There is no country where the art of constructing weirs across large rivers has been more deeply studied or so successfully practised as India. India can show the longest weirs in the world, and, with one or two exceptions, the highest ones. The construction of weirs of moderate height was successfully accomplished by natives long before English engineers came to the country to benefit by their experience, and to improve on their methods of construction. The Grand Anicut on the island of Seringham in the Tanjore district of Madras is a notable example of a native work which has successfully stood the test of time. That weir is 1080 feet long, and from 40 to 60 feet in breadth, the crest is 15 to 18 feet above the bed of the river.

This old work was built in a serpentine form across the bed of the Cauvery river; the natives who constructed it probably held the theory that it would be stronger in that form, as the channels of natural streams generally take that shape. The surface of this weir was originally intersected by rough channels at a lower level than the general crest: these were probably intended to act as rough under-sluices. It was not until the year 1830, when permanent under-sluices were constructed in this weir by English engineers, that it was discovered that the old weir, which is said to have stood successfully for 1600 years, was only composed of rough stones set in clay, and that no mortar of any kind, as had been supposed, was used in its construction.

The earlier examples of weirs constructed by natives are mostly those in which only boulders and large stones were thrown together to form the main body of the weir, the front slope of the weir and the crest for a short distance being hand packed. In some cases the crest stones were bound together by iron dogs. There are, however, some samples of weirs constructed by natives in masonry. There is also at least one example of a composite one, built on rock, the upstream face being of brick masonry, the downstream one of coursed rubble, the core of concrete, and the crest of granite ashlar.

There are six main classes into which Indian weirs may be divided:—

1. Weirs founded on rock.

2. Weirs in the boulder formation in the higher portions of rivers near the hills.

3. Weirs in clay or hard kunkur soils.

4. Weirs on sand of moderate depth with clay or rock below.

5. Weirs on coarse sand of great depth.

6. Weirs on fine micaceous sand of great depth.

Weirs of the first two classes are usually on rivers with a declivity of from 25 feet to 5 feet in a mile; those in class 3 on rivers with a slope of 6 feet to 2 feet a mile; and those of the other three classes on rivers having a slope of 2 feet to as little as 6 inches in a mile.

There are several well-known dangers which threaten all river weirs. There is, first, the danger of the weir being breached by the actual force of the current sweeping the materials of the structure away. Breaches may, in this way, be caused by the "pound" of the water falling on the floor of weirs having a vertical drop, or by the actual friction of the water passing over the materials forming the slope or talus below the crest, or by the velocity of the water carrying away the bed of the river below the weir and thus undermining the structure from behind. This danger is most common in the case of rivers having a rapid fall and subject, consequently, to rapid floods. A rapidly rising flood is more dangerous than one rising slowly, not only by reason of its greater velocity, but from the fact that the rapidly rising flood causes a greater head on the weir, that is a greater difference in level between the water above and that below it: the river bed has in that case less time to fill up and so form a "cushion" to protect the rear slope of the weir. A rising flood, be it a rapidly rising one or not, is always more dangerous than a falling flood, for the same reason. The breaching of weirs by the action of the water flowing over them is common to all classes of weirs, and it most commonly occurs by the undermining of the weir from below. This danger is to be guarded against by long floors or long tail slopes, and by the use of sufficiently heavy blocks of stone where the velocity is great.

A second danger to which river weirs are exposed is that of being breached by water flowing below them and undermining the foundation. This danger is not a common one in India as the head of water on the weirs is small, and the river beds above the weirs frequently silt up nearly to the crest-level, and all flow, immediately below the masonry, is stopped or reduced to a minimum by the staunching of the sand by the muddy silt. Weirs of the last three classes are more or less liable to be breached in this way; those of the last class are the most liable: the danger may be met by curtain walls sunk into the river bed below the general foundation

level of the weir, or by sheet piling; or it can be stopped, even in weirs with shallow foundations, by increasing the width of the weir so that the frictional resistance to the flow below it is increased.

A third danger is that a weir may be outflanked by the water in the river. This is most likely to occur in rivers with friable banks and especially when the course of the river above the weir is not straight and shows signs of change. It is desirable in those cases, where there is any probability of the river seeking to change its course, to keep the weir as low as possible, so that the afflux caused by it may be small. This danger is to be met by training works above the weir: these, in some Indian weirs, are of very considerable extent.

A fourth danger to which weirs across large rivers are subject, is that of parallel currents. These currents generally threaten the front face of a weir, they tend to undermine the foundations and thus breach the weir. They are generally due to the formation of islands in the bed of the river, which are caused by the gradual advance of the river bed itself and by the deposit of silt in the pond above the weir, where the velocity of flow is checked. There are few rivers, other than those in absolute rock, where there is not a more or less constant flow of the materials forming the bed of the river. In a river with a sandy bed this action is in some cases visible. As the water flows, so the bed flows, but more slowly. The grains of sand may be seen travelling forward when the velocity is sufficient to move them, and grain by grain the whole body of the river bed is slowly and intermittently advanced with the varying velocities of the stream.

The same action is not only visible but is actually audible in rivers in the boulder formation: in these rivers the flow of the boulders in a heavy flood may often be plainly heard as the stones pass over the floor of the under-sluices of weirs. In some cases it has been found necessary to cover the noses of piers in these rivers with timber to protect them against the constant blows of the boulders. When a weir has been constructed across a river it acts as a bar to this forward motion of the river bed, and, gradually the advancing sand or shingle rises to the level of the crest, or even above the crest of the weir. Plate XLI., page 142, shows this result in the case of the upper Coleroon weir in Madras, where the river bed has been raised in a very marked manner. This weir is in two lengths: the northern one is 393 feet long and 7 feet high, and the southern one 1736 feet long and 5 feet high. There is a series of sluices at frequent intervals in this weir: the northern weir having a central set of 48 lineal feet, and the southern weir six sets of sluices of 111 lineal feet: the

waterway of the sluices is about one-twelth part of the obstruction offered by the weir. But these frequent sluices have not impeded the rise of the river bed and have produced little effect except that local channels have been cut through the sand above the weir down to the level of the floor of the sluices. It is believed that there are few instances in which a weir has been pierced at such frequent intervals: but there are many instances in which it has been proved that the scouring effect of even the most powerful sluices is comparatively small, in checking the general rise of the bed above a weir. Such sluices will maintain a channel through the deposits above the weir in their immediate neighbourhood, and this channel may run back a sufficient distance to enable the low level supply of the river to be drawn into it. But the only certain way of constructing a weir which will not raise the bed of the river above it, is to keep the crest low and to raise the level of the pool in the dry season, by shutters, or needles, or a movable dam of some kind on the crest of the weir. In those cases where canals take off on both banks of a river above a weir, and it is desired to maintain a navigable channel between them, this silting of the river above the weir may seriously impede navigation. It has done so in the case of the Sone weir in Behar, and to a smaller extent in the Mahanuddee in Orissa. But a more serious result is that the gradual raising of the bed may interfere with the supply of the canal in the dry season; for, as the deposit above the weir increases, the effect of the under-sluices in maintaining a deep channel through those deposits becomes less and less effective. The channel will always be kept clear to the level of the floor of the under-sluices in their immediate neighbourhood, but the bed of it may be so raised, some distance above the weir, as to interfere with the discharge in the dry season. It will then be necessary either to dredge this channel or to raise the weir crest temporarily. The plan of raising the weir crest by shutters,* which are put up in the dry season, and laid flat on the weir crest in floods, has been adopted in several cases in which it had been originally supposed that the level of the crest of the masonry weir would have been sufficient to have ensured the supply. If the raising of the river bed above a weir were uniformly distributed along the face of the weir, there would be no disadvantage in it as regards the stability of the weir, but this rarely or never takes place. The bed fills up unevenly and sometimes a main channel is left, which is so narrow that a high

* Such shutters have been erected on the weirs which supply the Sone Canals, the Sirhind Canal, the Orissa Canals, the Lower Ganges Canal, and in other cases.

velocity is induced in it which is injurious to the weir at the point where the stream impinges upon it.

The accretions in the bed of a river above a weir, are not, as a rule, uniformly distributed. The currents of the river vary in intensity and direction in different stages of the floods, and they carve out channels in the moving bed: between these channels, islands gradually rise on which grass and brushwood take root in the dry season. This vegetation checks the velocity of the next flood, and silt is deposited, year after year, until the island rises up to, or nearly up to the highest flood-level. In the river bed above the Sone weir in Behar, there are many such islands which are 8 or 10 feet above the original level of the river bed, and which are regularly used for pasturing cattle. The islands which are formed in this manner become sufficiently stable to influence the flow of the river, and they may be so disposed that, more especially in falling floods, they may cause currents parallel to the face of the weir, which, if not stopped, may be dangerous. It is frequently necessary to throw out stone groins at right angles to the line of the weir to check such parallel currents.

It must not be assumed that the silting up of the bed of a river is the invariable result of the construction of a weir. There are instances to the contrary, more particularly if the weir is situated in a narrow gorge of the river where an increase occurs in the velocity of the stream. The velocity above, and over, the weir may then be sufficient to prevent any deposit. Generally speaking, it may be said that the bed above a weir in the boulder formation, or where the bed is of coarse sand, is almost certain to be raised up to, and even above the weir crest. But the finer the sand and the more muddy the silt in the river, the less likelihood is there of a rise in the bed above the weir.

Dangerous parallel currents may be induced in front of a weir by a faulty alignment of it. In almost every case, as has been already stated, a weir should be placed at right angles to the axis of the river on which it is built, unless it is on rock or in the boulder formation. This should invariably be done where the bed of the river is liable to erosion. A weir set diagonally across a river is obviously liable to be exposed to a parallel current along the upper face; for the water impinging on the diagonal face will be diverted towards the lower end of the weir. A weir built on rock may withstand this action, but in other cases it is dangerous. In one case where a weir (the Naraje weir in Orissa) was built diagonally across a river with a hard sandy bed, it was found necessary to protect the weir wall, at considerable expense, by immense

masses of rough stone thrown on the upstream side of the wall: the weir wall has, on more than one occasion, been undermined by the action of the parallel currents and the piers of the under-sluices have been completely overthrown, possibly by the same force.

Another of the dangers which threaten some river weirs and which may be a serious one, is that of a retrogression of levels in the bed of the river below the weir. It has already been explained (page 93) how, in certain portions of a river's course, after it has emerged as a torrent from the hills, the velocity of its waters is too great for the soil and an action is constantly going on which gradually deepens the level of the bed and reduces the surface slope until the velocity is suitable to the soil in which the river flows. If a weir be constructed across a river in which this action is in progress, it stops it at and above the weir by forming a bar to further cutting of the bed at that point. But the cutting action below the weir is not checked, and the bed of the stream is gradually cut away, it may be at a very slow rate, but still by small degrees the head on the weir is increased and the toe of the talus of the weir is attacked. In such cases the only remedy is to continue to strengthen the weir as it may need it, by increasing the length of the rear slope, or by constructing subsidiary weirs below the main one to check the retrogression: this plan has been adopted on the Eastern Jumna Canal below the dams built on torrents crossing that canal which had been injured by this action.

CHAPTER VIII.

HEAD-WORKS IN ROCK AND BOULDERS.

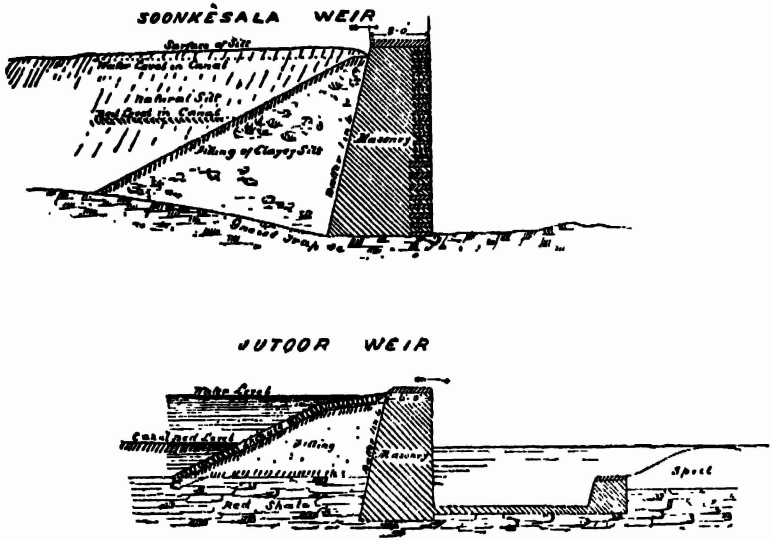
Soonkesala Weir—Betwa Weir—Afflux of 6 or 8 feet on Betwa Weir—Under-sluices of the Betwa Weir—Head-sluice, Betwa Canal—Ravi Weir of the Bari Doab Canal—Training Works in the Ravi—Site of Head-works of the Bari Doab Canal not well selected—Under-sluices of the Ravi Weir—Under-sluice Gates of Ravi Weir—Head-sluice of Bari Doab Canal—Head-works of the Eastern and Western Jumna Canals—Under-sluices of the Jumna Weir—Head-sluice of the Western Jumna Canal—Jumna Weir—Regulation of Eastern Jumna Canal—Faizabad Dam—Khara Spur at Head of Eastern Jumna Canal—Ganges Canal Head-works—Temporary Dams at Head of Ganges Canal.

ONE example of a weir on a rocky bed is the one across the river Toombudra at Soonkesala in Kurnool. This weir forms the head-work of the Kurnool Canal, which was constructed by the Madras Irrigation and Canal Company * in 1866–70. It has a total length of 4500 feet of clear overfall: the average height of it is 18 feet, but it varies from 6 feet to 26 feet in different parts of the river bed. The more lofty parts of the weir have the section as shown in the sketch on next page; in these parts the wall is of solid gneiss rubble masonry faced with limestone ashlar: the upstream side of the wall has a batter of 1 in 4, the downstream face being vertical. The lower parts of the weir have the same width of crest, but both faces of the weir wall are stepped to a batter of 1 in 8, and in these parts the wall is either of rubble masonry or of gravel concrete with gneiss rubble facing. The whole length of the weir is coped with limestone 12 inches thick, every alternate stone being 8 feet in length, and weighing about 1½ tons. The rock of gneiss and trap, on which this weir is built, appeared perfectly sound and hard at the time the weir was erected. The sequel, however, has shown how necessary it is to exercise great care in bedding a weir with a vertical overfall. In this case the force of the scour was sufficient to dig out several deep holes in the rock, which had to be built up with masonry in cement.

The Jutoor weir on the same canal is built across the Kali river,

* 'Proceedings of the Institution of Civil Engineers,' vol. xxxiv.

which has a bed of soft shale. The weir is 6 feet broad on the crest, has a batter of one in four on the upstream face, and is vertical on the downstream side. Below the weir an ashlar floor of limestone is laid to protect the shale from the scour of the overfall. The floor, which is recessed below the river bed, ends in a dwarf wall, so that a water cushion



WEIRS ON THE KURNOOL CANAL IN MADRAS.

is formed which aids in the protection of the floor. Experience has shown that in this case the length of the floor is insufficient. The weir is protected on the upstream side by a bank of broken shale revetted with shingle.

The weir across the Betwa river in the North-West Provinces is a great contrast in design to those just described. It is founded on gneiss rock, and built of rubble masonry. The weir was designed to support the entire pressure from above in time of flood, on the supposition that the channel below was dry. The greatest height of the weir is 51 feet for a short length, and there is a considerable portion of it over 30 feet in height, as will be seen from the longitudinal section on Plate XXVII.

The head-works of the Betwa Canal are situated on the river Betwa, about 15 miles from Jhansi, in Bundelkund, in the North-West Provinces. The river has a course of about 360 miles from its source in Bhopal to the Jumna river, which it joins near Humeerpore. The catchment area of the river above the Betwa Canal is about 8992 square miles, and the maximum flood discharge has been calculated to be 750,000 cubic feet

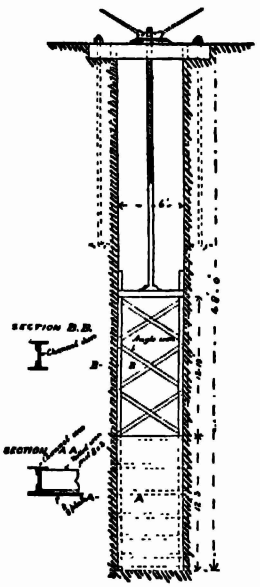
a second.* This discharge is said to be due to the flow-off of as much as 80 per cent. of the rainfall, which appears a large percentage on so extensive an area even on the rocky ground which forms the greater portion of the catchment. The slope of the river bed immediately above the weir, which has been constructed across the river, is only about 0·09 per thousand, or some 5 inches a mile, but the slope of the water surface in high flood averages 2·8 feet per mile, or 0·5 per thousand for a distance of ten miles above the weir, and, immediately above it, the surface slope in floods is as much as 4·5 feet a mile. Before this weir was built, the bed of the river, in the dry season, was a series of long ponds, some as much as three miles in length, from which a mere trickle of water passed forward. Immediately below the weir the fall of the bed of the river is much more rapid: for the first three miles it is over 9 feet in the mile, so that the site of the weir is a very happy one, in that a large body of water can be impounded above the weir in the flat reach of the river. This storage above the weir is an essential part of the scheme of works, as the discharge in the river in May and June is entirely wanting. The level of the weir crest is 631·50, which, as will be seen from the longitudinal section in Plate XXVII., makes the height of it in the deepest part of the river bed more than 50 feet. The bed of the river at the site of the weir, and for a distance of half a mile or more below it, is good homogeneous gneiss rock. The weir is divided into two lengths by an island, on the eastern side of which the river bed is itself a natural weir, the rock in one place rising above the weir crest. The weir obstructs about 60 per cent. of the waterway, below the former flood-level of the river, and the result is an afflux which has been calculated to be from 6 to 8 feet. The calculated flood-level above the weir is 648·00, which gives a depth of 16·5 feet on the crest of the weir in maximum flood. In such a flood the level of the river below the weir is about 640·00, consequently the crest would be submerged about 9·5 feet. The afflux caused by the weir has necessitated the construction of an afflux embankment on each bank of the river, as shown in the plate. These embankments have a width of crest of 20 feet, and are revetted with stone in parts. At a short distance below the main weir two subsidiary weirs have been constructed, one in each of the channels on either side of the island. These weirs have their crests at 610·00, which is two feet above the floor of the under-sluices, so that there is always a cushion of water below the main weir, the surface of

* 'Report of the Chief Engineer, Irrigation Works, N.-W. Provinces,' dated 2nd Nov., 1874, para. 38.

which is 21½ feet below the weir crest. These subsidiary weirs are of short length (300 feet or so), as the channels below the main weir are narrow.

It was anticipated when the head-works of this canal were constructed that there would be such heavy deposits of silt above the weir that it would be difficult to maintain a channel to the head-sluice of the canal. The velocity of the river in floods is about 7 or 8 feet a second only, which is not sufficient to move boulders or large shingle, and there is little material of this nature in the river nor is there much coarse sand. The silt which is carried by the river seems to be generally of a fine nature which would be largely carried forward by the flood velocity, although a certain quantity would inevitably be deposited in the pool above the weir. In order to give a great power of scour in front of the head-sluice, a longitudinal wall, or river wing, has been constructed in the river bed for a length of 200 feet in front of the head-sluice and 36 feet from it, which confines the draught of the under-sluices within a channel immediately in front of the canal head. The under-sluices have four vents, each 6 by 12. The maximum discharge through the under-sluices would occur when the flood-level above the weir was a foot or so above the weir crest, and before the level below the weir was appreciably raised by the discharge of the river: in that case a velocity of 25 to 30 feet a second would be obtained through the under-sluices themselves, and would be maintained for a few feet in front of the sluice, but would be gradually reduced as the full waterway of the channel, which is defined by the river wing and the face of the head-sluice wall, came into operation: at the head of this channel, which is 200 feet from the under-sluice, the waterway would be about 36 feet by 25 feet in depth, or 900 square feet, which is about three times that of the under-sluice vents, so that the velocity at the head of this channel would be from 8 to 10 feet a second. This is ample to remove all silt and sand but is insufficient to move shingle the size of apples near the head of the river wing wall. The level of the floor of the canal head-sluice is 610·00, and the floor of the under-sluice is 608·00, which gives an additional advantage in excluding sand or other material which may be carried along the bed of the river. As the water below the weir is maintained at 610·00 by the subsidiary weir, the maximum head on the under-sluice is (631·50 – 610·00) 21·5 feet when the reservoir is full. This head would be reduced in flood time rather than increased as the level of the water below the weir would rise more rapidly than the level above it. The under-sluice is fitted with two sets of draw-shutters

working in grooves. The upper shutters are of iron and the lower ones of wood. The upper ones run in cast-iron grooves without friction rollers and are lifted by a screw 6 inches in diameter fitted with capstan bars in the nut-head, as shown in the sketch. The gates are very hard to move: it takes nine or ten men to move them under a head of 20 feet. The lower gates are drop-gates, they are of sâl wood 8 inches square, bound with heavy angle irons at the corners. They are intended partly as a safe-guard in case of any accident to the iron gates, and partly as an aid in raising or lowering the upper gates when great heads have to be dealt with. The top of the drop-gates would never be far below water, but an arrangement has been fitted to them by which they can be fished from above and lifted by the travelling winch which runs above them on the crest of the under-sluices. When the drop-gates are lifted they are suspended on to let-go gear which can be easily released with a blow when it is desired to drop them: these gates, however, have not been much used: it is difficult to get them down, owing to the great velocity of the stream below. The under-sluice is most strongly built in cement.



UNDER-SLUICE GATES, BETWA CANAL.

The head-sluice is also a remarkably strongly built work; it is founded, like the weir and under-sluice, on rock. The floor of it is 610·00 and the water-level of the canal is 623·00, so the maximum head is 25 feet with a flood at 648·00. The water can be drawn into the canal through two lines of vents. The upper line is used when the water in the reservoir is high: the lower line when the level has fallen so far that the discharge from the upper line is insufficient. This draught from the surface reduces the silt carried into the canal. The vents are fitted with iron draw-gates: each gate covers an opening 6 feet by 6 feet. The top of each opening is arched. The gates are lifted by screws with capstan nuts: the screws of the upper and lower line of gates are only separated by a few inches, so that the upper gates must be depressed on to their seats before the lower gates can be lifted: the capstan heads are moved from the nuts of the upper to the lower gates when a change is necessary. In addition to the draw-gates in the head-sluice, there are two inde-

pendent lines of drop-gates (as shown in the section A B, Plate XXVIII.), one set is above the vent which runs through the sluice, and the other is below it: they cover openings 10 feet high by 6 feet broad, and are of timber, similar to the drop-shutters of the under-sluices. The upper line of drop-gates runs in cast-iron grooves, but the lower ones in stone grooves only. A travelling winch runs on rails above for lifting the drop-gates: this is far less powerful than the one on the under-sluice. Both in the case of these gates and in those of the under-sluices an arrangement has been made so that they can be jumped down on to the floor if they fail—as they do in a strong current—to reach the floor by their own impetus when they are released from the let-go gear which holds them above. On the top of each gate two short timber ends can be fitted into sockets formed by the angle irons with which the gate is bound: there is a spare gate, similar in every way to those in place, which can be placed by the traveller in the groove above the one which it is required to jump down. This upper gate is lifted by the traveller, put on the let-go gear and then released. It acts as the monkey of a pile-driver in forcing the lower gate down, falling each time on the timber ends of the lower gate.

The weir across the rocky bed of the Nira river at Vir in the Bombay Presidency has some features in common with the weir on the Betwa. A description of this work has been given in Chapter V.

The weir across the Ravi river at the head of the Bari Doab Canal in the Punjab is an example of a weir of the second class in the boulder formation. The weir itself is simple, and is only 3 feet above the original river bed: it is substantially as shown in Plate XXIX.: in parts where the river bed was deep the weir wall was carried down to it. High floods rise to about ten feet over the weir crest. The wall itself is in boulder masonry, and it shows what good results can be obtained with small stones, provided they are thoroughly well set in good mortar. This wall is built with comparatively small boulders, hammer-dressed on the surface, thoroughly well bedded in mortar, and although there have been several accidents to the weir this wall has stood well. The velocity over the weir in flood is said to be 15 or 20 feet a second, and the mortar joints are much scoured out by the water and sand, but the stones are rarely displaced. The slope of the river bed above the weir is over 20 feet in the mile, and boulders the size of a man's head are carried down it. A plan of the head-works is given in Plate XXX.: originally the head A was the only regulator and there was a weir wall across the channel D B X at B. It was

found that the channel D B was frequently blocked with the shingle which was brought into it by the great velocity of the water. A regulator was then constructed at the site of the weir wall at B, so that the velocity of the indraught at the head could be controlled, but the difficulty in keeping this channel open still continued, and it was found necessary to construct the weir across the river, with its under-sluices and the head-sluice at D. The regulator at B had 21 openings of 15 feet, but 15 of the openings have been permanently closed up since the head-sluice was built and only six openings are used now as escapes to the supply channel. There has been considerable difficulty in this case in keeping open a channel in front of the head-sluice: heavy training works have been required in the river bed above the weir to direct the cold weather channel towards the left bank. The movement of shingle in the river is considerable and the weir itself is now completely buried in parts by shingle and boulders. The training works consist of a series of embankments and spurs, which were at first constructed as bunds faced with boulder pitching, but this did not stand and considerable portions of some of these spurs are now in masonry. The result has been successful as there is now a good channel leading to the under-sluices, and, in the dry season, the entire discharge of the river is passed into the canal.

In this case the selection of the site for the head-works of a canal from the Ravi river was not a happy one. The site was higher up the river than was necessary in order to utilise the available water supply. The great velocity in the river and the flow of shingle and boulders has caused great trouble and expense, and the cost of the construction of the canal itself has been high owing to the very rapid fall in the country. The canal takes out from the river in 53 feet of cutting and it is a very pretty piece of work: the soil is full of boulders and the deep slopes at the canal head are neatly revetted, in steps, with them. The slope of the bed of the canal in the first 12 miles is (1 in 1250) 0·8 per 1000 and the depth of water from 4½ to 5½ feet: the bed width is 112 feet: the maximum discharge was designed to be 3700 cubic feet a second, but larger quantities are now passed: the velocity rises to as much as 5·7 feet a second. Although the canal has this steep slope the bed of it comes to the surface within three miles and a little irrigation is effected in the fourth mile. But the slope of the country is so rapid that in the first 12 miles of the canal the bed level drops more than 200 feet, of which 150 feet is obtained by 19 rapids or weirs constructed in the canal and the rest by the slope of the canal bed. The cost of the construction

and maintenance of these works has been great, and little or nothing has been gained by tapping the river at so high a level, and then dropping the water by fall after fall and rapid after rapid down to the point where the slope of the country is more suitable: nothing at least except beauty: the first 12 miles of the Bari Doab Canal is perhaps the prettiest piece of canal scenery in the world. The channel winds about through beautifully wooded banks in a shallow stream paved almost with boulders: round nearly every curve a new rapid of foaming water comes in view, and the stream, flowing with the great velocity it has, is bright and gay. Most of the curves are revetted with boulders to protect the banks from erosion and at every few yards there are signs of the care and skill which has proved to be necessary to deal with such high velocities. Some 10 or 15 miles lower down the Ravi river, the slope of its bed is much less, and, although the width is greater, the head-works at that site would probably have cost less money: it would have been possible to have commanded an equal area of land, and very nearly the same land, with less original cost and less expenditure in maintenance.

The under-sluices in the Ravi weir have been the result of experience: they now consist of twelve openings of 20 feet each. They were originally constructed with smaller openings and low piers with grooves, which it was intended to operate with *kurries* as they are called in the Punjab, that is, simple baulks of timber, dropped horizontally into the grooves. The piers were not successful, they were knocked over and the under-sluices were reconstructed substantially as shown in Fig. 2, Plate XXIX. But the boulders in crates and the lower boulder wall were destroyed by the scour, and, about 1876, the toe of the under-sluice floor was reconstructed as shown in Fig. 3. In 1885 an accident occurred: the toe of the under-sluice floor was undermined and the floor fell in as shown in Fig. 4, and the wing wall between the under-sluices and the weir was sheared clean through in the same manner. The floor was then greatly strengthened, as shown in Fig. 5; the wing wall on the river side was raised and extended; and a groyne of gravel and boulder pitching was constructed as shown in Fig. 6, in continuation of the river wing between the under-sluices and the weir itself.

The heavy action on the floor of these under-sluices, which has necessitated frequent and heavy repairs, is increased by the training works above the weir which throw the full force of the stream towards the canal head, and tend to diminish the portion of the flood passed over

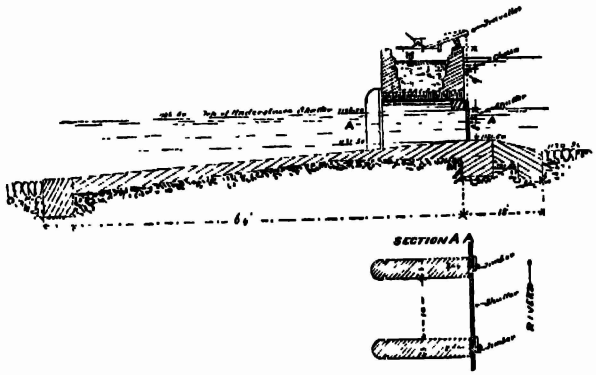
the weir itself, and to increase the portion which passes through the under-sluices. The weir, as has already been stated, is partly buried by shingle and the bed of the river is generally filled up to the crest level. It is not improbable that the increased strength which has been required is due to some extent to a retrogression in levels (page 115) of the bed of the river below the weir. The under-sluices are very strongly built, the floor, which is of hammer-dressed boulders, is remarkably good and stands the enormous velocity in a wonderful way, the stones are rarely more than 14 inches or 16 inches square, but they are very hard, and thoroughly well set in mortar: this floor has stood much better than some others which were constructed of large ashlar blocks. Owing to the flow of boulders through these under-sluices it was found necessary to face the lower portion of the noses of the piers with baulks of wood and the upper parts with sheet iron. It is said that the flow of the shingle and boulders over the floor can be distinctly heard in a flood.

The under-sluice gates are in two rows: the lower range are 3 feet and the upper range 4 feet in height: baulks can be dropped in above the upper gate. The gates are fitted in separate grooves parallel to each other and are lifted horizontally by fixed gearing on the piers above. The gates are of iron and are very similar to those used on the Chenab Canal (page 176) and on the Sirhind Canal. It is found very difficult to get the lower gate down when it is dropped: this is said to be due to the lightness of the gate, but there can be no great difference between the weights of these gates and those on the Sirhind Canal weir where this difficulty does not occur, and the cause is probably the greater pressure brought on the gate by the higher velocity in the stream.

The head regulator, or head-sluice, on the river face has twenty-three openings of 10 feet each: the sill is at R.L. 1131·50 or 2 feet above the under-sluice floor: the vents are only 5 feet high to the springing of the arch and are closed by wooden shutters which are raised by a travelling crane. The peculiarity of this sluice is that there are no noses to the piers on the river side, and that there is only one groove, on the up-stream side, to guide the shutters. This groove is formed of timber as shown in the sketch below: it is believed that this arrangement was dictated by the damage done by the flow of the boulders in floods.

The floods in the Ravi are sudden, violent, and generally of short duration: the fall of the river is great and the rainfall on the hills above is quickly discharged. In order that no excessive strain may be thrown on the under-sluice floor it is necessary to watch the river, during the months of July to October inclusive, very closely, and to work the

under-sluice gates frequently. If the gates are not opened when the water begins to rise the flood will make until there is a dangerous over-fall over the shutters, and it may become very difficult if not impossible to lift the lower gates. On the other hand if the gates are kept open too long, perhaps in anticipation of a flood, the supply in the canal, which at



SECTION OF HEAD-SLUICE, BARI DOAB CANAL.

this time of the year requires to be well sustained in order to supply the *khareef* (wet season) crops, falls too low. Very strict rules are enforced during these months: double sets of men are employed on the under-sluices; sentries with lanterns are kept walking up and down the bridge over the under-sluices all night; an officer of the engineer establishment is required to inspect the weir every night between ten and four o'clock, and has to sign a certificate that he has done this.

The head-works of the two canals, called the Eastern and the Western Jumna Canals, which take off the Jumna near the point where that river debouches from the Sewalik range of hills, are in the boulder formation. Both these canals were originally supplied by temporary dams or spurs which were annually constructed in the boulder bed of the Jumna and one of them is still supplied in that manner. The two canals are under different administrations: the Eastern Jumna is in the North-western Provinces and the Western Jumna in the Punjab. At times the entire discharge of the river is taken into the two canals and the equitable division of the total available supply, used, occasionally, to be a source of difficulty between the Governments of the two provinces. It was partly to avoid these difficulties, but mainly in order to supply the canals with less annual labour and risk, that a set of permanent head-works was constructed, some sixteen years ago, across the river. These works now form the source of supply of the Western Jumna canals, but they have never been used with reference to the Eastern

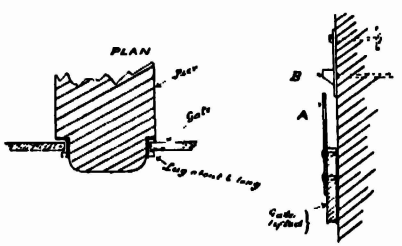
system, which is still supplied in the old manner, which will be presently described.

The permanent head-works are shown in Plate XXXI., and a reference to Plate XXXIV. page 130 (which shows the head of the Eastern Jumna Canal) will make the general arrangement more clear. Advantage has been taken of an island in the river at the site of the permanent head-works, which was largely increased in size by the excavation of the channel below the under-sluices; on each side the banks of the island are heavily revetted by boulder pitching, with a masonry toe to the slope, and the nose of it is protected by a strong revetment wall of boulder masonry from which the weir takes off. The weir is built diagonally across the river, and the crest of it is not horizontal but is sloped from the upper to the lower end: the level of the crest at the east end is 1069·00 and at the west end 1063·75. The fall of the river bed is 16 or 17 feet in the mile. The eastern under-sluice, which was intended to have been worked to keep a channel open in front of the East Jumna Canal head-sluice, which is immediately above it, has seven openings of 21 feet, the floor level being 1061·00 and high flood about 1078·50. These under-sluices are completely blocked with shingle, which has accumulated up to the level of the weir crest and in front of the head-sluice. The under-sluices appear insufficient to maintain a channel in front of the sluice, but they are not regularly worked, as the head of the Eastern Jumna Canal is not used: a channel 50 feet broad was excavated one year through the shingle to these under-sluices, but it filled up again in the floods.

The western under-sluices consist of ten openings of 20 feet and eight openings of 23·16 feet; the floor level is 1052·5 and the depth of water in flood about 17 feet over the floor; these sluices, at the lower end of the weir, have proved amply sufficient to maintain a channel in front of the head-sluice, and eight of the openings on the side next the island are built up to a height of from 6 to 8 feet. A section of the under-sluice floor is given in Plate XXXII.; it is not as strong in design as the floor of the under-sluices on the Ravi weir, and the work does not appear as strong in itself; the floor and walls are constructed of boulder masonry, but the boulders in the Jumna weir are not hammer dressed as those in the Ravi weir are; the floor is not as thick, and the width of it is 75 feet as compared with 115 feet: the depth of water in each case is much the same, but the flood discharge of the Jumna is believed to be larger than that of the Ravi. These under-sluices on the Jumna show no sign of pooling below the floor, indeed the shingle has accumulated below them.

The under-sluice shutters are of iron similar to those on the Chenab Weir (page 176); there are two shutters in every vent, each spanning the opening of 20 feet; each shutter is 4 feet 3 inches in height and runs in a separate pair of vertical cast-iron grooves built into the piers; the upper shutter overlaps the lower one when it is down, by 6 inches, so that the crest of the two shutters is 8 feet above the floor. There is a chain permanently attached to each shutter, so that it is not necessary to fish for the eyebolt when they have to be raised. The shutters are lifted by a traveller running on rails on the piers. There is sometimes a difficulty in getting them down, they are bumped down with a long pole or *bullah*.

The head-sluice of the West Jumna Canal, Plate XXXIII., stands immediately above the under-sluices; the level of the sill is 1056·5, or 4 feet above the under-sluice floor, a measure which is designed to prevent the flow of boulders into the canal. The steep slope in the floor of the head-sluice is peculiar. There are 35 openings of 6 feet, and the piers are 3 feet 6 inches thick; they have very short noses, like the piers at the head of the Bari Doab Canal. The gates are of timber, worked by a traveller above. The gate grooves are peculiar, as shown in the sketch; they are of iron, with only little lugs in front to retain the gate. The head-sluice gates are hung, when they are lifted, by a piece of flat iron attached to the gate: the flat iron A has a slot cut in it which fits on to the catch B. The gate has sufficient play to enable the flat iron to be moved on and off the catch, so that when the gate has to be dropped it is only necessary to push the flat iron off this catch with a lever and it falls. There are chains permanently attached to each gate for lifting it; these, when the gate is hung on the catch B, are hooked on to staples in the wall, so that they are clear of the gate when it falls.



GATE GROOVES OF THE HEAD-SLUICE, WESTERN JUMNA CANAL.

The weir itself is similar in construction to the Ravi weir, except as regards the depths of the foundations, the cross section of it being as shown in Fig. 7, Plate XXIX. The crest of the weir was raised 6 feet above the general level of the river-bed, but the bed above has filled up with shingle, and at least half the weir is now covered with boulders and shingle over the top of the crest; it is covered in this manner more or less at each end, but the centre is clear. It is sometimes necessary

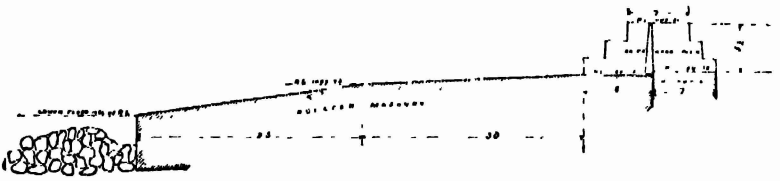
in the cold weather to make a cut through the heavy shingle deposits above the weir, to lead the water of the river to the head-sluice, even although the sill of the head-sluice is nearly 8 feet below the western end of the weir, a fact which shows how powerless under-sluices are to influence the stream of a river for any great distance above them.

The supply of the Eastern Jumna Canal was originally drawn from the river near Faizabad (Plate XXXIV.), but in 1834 the bed of the river near this point retrograded to such a degree that the source of supply was removed to Khara, and a dam was constructed at Faizabad across the channel which used to supply the canal. The channel from Khara to Faizabad is a portion of the bed of the old Budhi Jumna river, which had only to be excavated near the head at Khara to make it suitable to carry the supply of the canal. In order to force the discharge of the river, or so much of it as may be required, into this channel, a spur is run out every year into the river near Khara immediately below the off-take. This spur is made in October or November, and is destroyed every year by the first or second flood in June and July. During the flood season the supply drawn in at Khara is more than ample, and a large volume of it has to be returned to the Jumna, either over the dam at Faizabad, or over a corresponding dam at Naushera, across the Budhi Jumna river, which forms a flood escape for the upper channel. At this point, Naushera, just below the dam, there is a regulator across the canal, by which its discharge is controlled. The upper, or Faizabad dam, is situated about two miles above the permanent weir across the Jumna, which is the head of supply for the Western Jumna Canal, and any water which is returned to the river from the Eastern Jumna Canal flows down to the permanent weir, and is available for the Western Jumna Canal. It thus occurs that the Faizabad dam is used, when the river is very low, to aid in the division of the total available discharge between the two canals: the total supply at such times is divided in the proportion of one-third to the eastern, and two-thirds to the western canals. If the action of the Khara spur at the head of the eastern system forces a larger proportion than one-third of the total volume into that system, the shutters or the *kurries* in the Faizabad dam are opened, and an increased supply is sent down the river to the head-works of the other system. The Khara spur must be made up to a certain point, or the eastern system will not get its proper share of the water; so the length of this spur is primarily the dividing power, and the Faizabad dam is used to correct minor inequalities.

The Faizabad dam appears to play an important part in flood time;

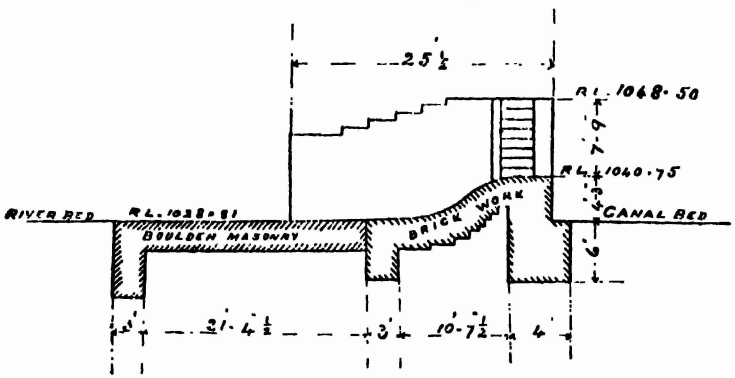
it acts as an under-sluice, and takes back to the Jumna a considerable volume of water. It might be expected that the channel from Khara to Faizabad would have become filled up with boulders and shingle, but this is not the case, although there must be a flow of shingle down the river-bed itself, and probably down the canal channel also. The slope of the channel is about 13 feet a mile from Khara to Faizabad, and 16 feet from Faizabad to Naushera, and it is thought that the fact that the channel does not deteriorate is due to the action of the two escapes, which carry back to the river the shingle which enters at the head. It is certain that a considerable amount of heavy detritus does pass over the Faizabad dam, for the floor is injured and cut about by the flow of boulders.

The Faizabad dam consists of a weir, with piers above it; the piers are 6 feet above the weir crest. There are twenty openings of 10 feet. In each opening a gate is hinged at its lower edge on the floor; the gates are held up by let-go gear, and when released they fall down stream and lie on the weir crest in flood time. There are grooves above the gates in which kurries or horizontal baulks can be inserted. The following sketch gives an idea of this work:—



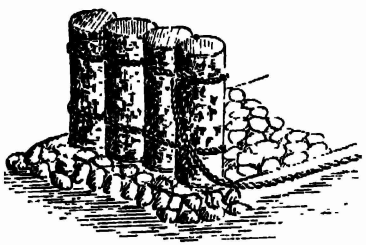
EASTERN JUMNA CANAL, SECTION OF THE ESCAPE SLUICES AT FAIZABAD.

The Naushera dam has a different section, as shown below; it is not subjected to such heavy floods as the Faizabad dam, and the depth of water on the crest rarely exceeds 5 feet.



EASTERN JUMNA CANAL, SECTION OF WEIR AT NAUSHERA.

The spur at Khara, which really forms the head-works of the Eastern Jumna Canal (which irrigates some 250,000 acres of land) costs a trifling sum—something like 1000 rupees—yearly. It is made of gabions full of boulders. The gabions are constructed of green twigs bound together with rope made of green grass; they are about 5 feet high, and 2½ to 3 feet in diameter. Four of these gabions are bound together with strong rope, also made of green grass, and, the lower ends of them being closed up with a network of twigs and rope, they are taken to the end of the spur and stood on end, as shown in this sketch.



GABIONS IN THE KHARA SPUR.

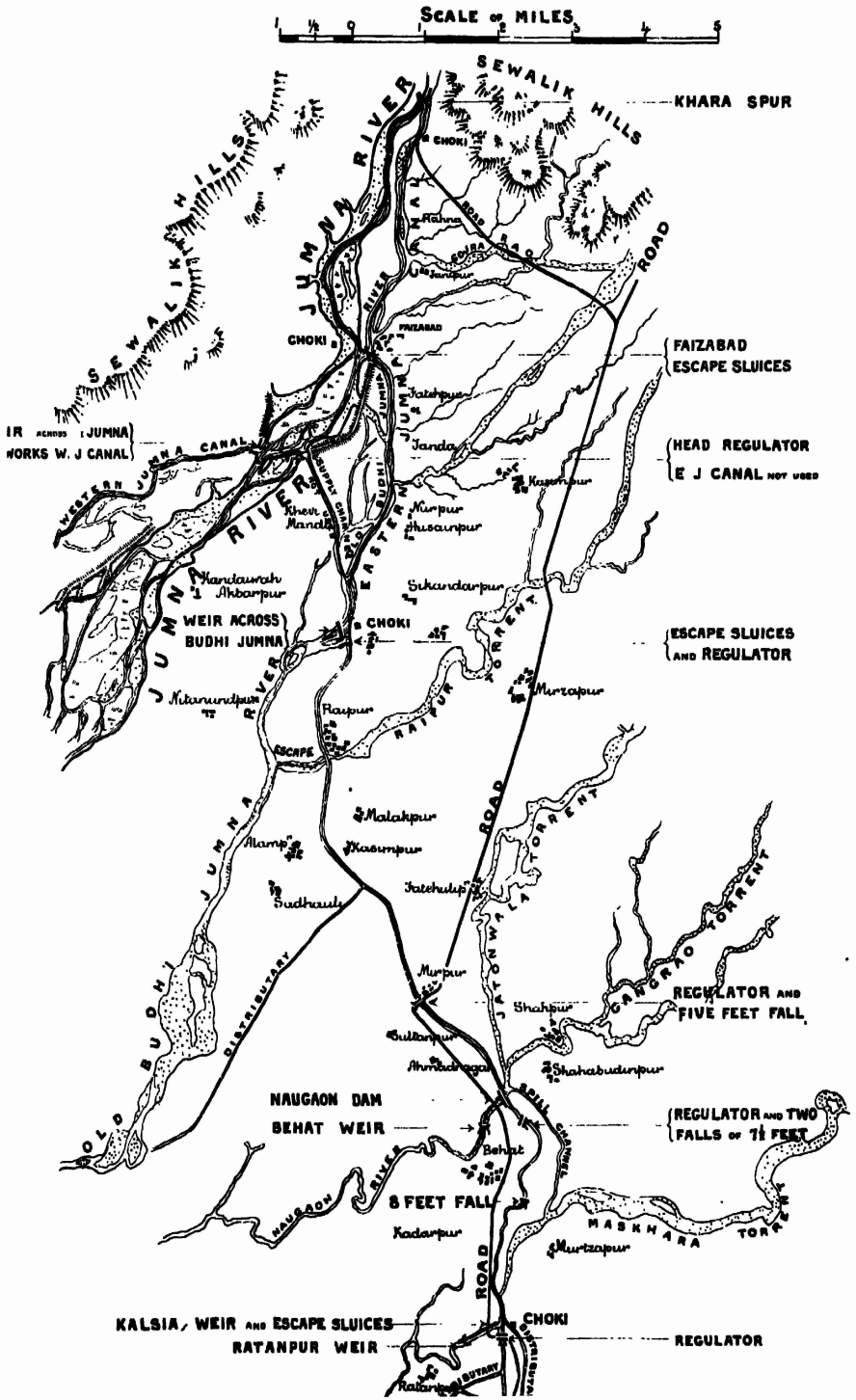
A strong rope, perhaps 3 or 4 inches in diameter, made of the same grass, which grows near, is attached to the group of four gabions, and made fast to other ropes at a point perhaps 30 or 40 feet from the end of the spur where the gabions stand. They are then filled with boulders and the tops are strongly bound over. The group of gabions is then upset by a body of men, and they fall over into the water. The stream is so strong that they would be swept away but for the rope by which they are attached to each other and to the other ropes of previous groups of gabions of which the spur is made up. In this manner the spur is advanced in 9 or 10 feet of water flowing at a velocity of 10 to 12 feet a second.

The Ganges Canal, which carries a maximum discharge of 6800 cubic feet a second, is supplied in a manner which has features in common with the system employed on the Eastern Jumna Canal. The supply, in the dry season, is forced into a side channel by temporary dams, and there are escapes from this channel back to the main stream of the Ganges. The head-works of this great system of irrigation are situated close to the hills where the river runs on beds of boulders, with a fall of some 10 feet in the mile. The Ganges at this point consists of several channels, which have changed considerably since the works were opened, and which are constantly changing more or less every year. The sketch on the next page, which is only approximately correct, gives an idea of the locality.

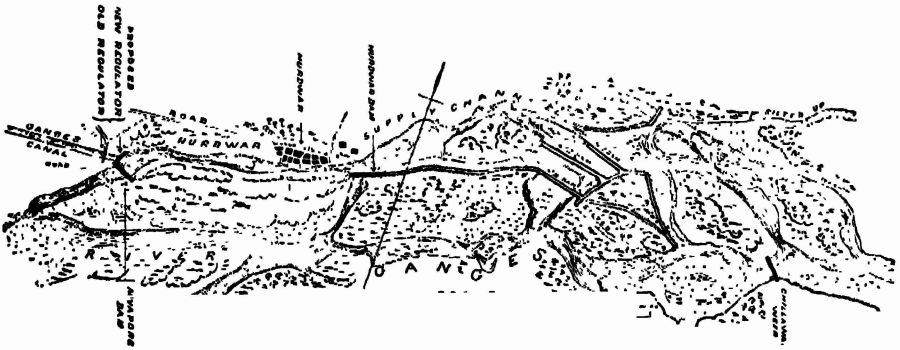
The supply of the canal is forced by a series of dams, which will be presently described, into the Hurdwar supply channel, which has two escapes on it: one is the Hurdwar dam, opposite the town of that name, and the other is the Myapur dam, which is close to the real head of the

EASTERN JUMNA CANAL

FROM HEAD TO NAGLA FALLS



canal, across which there is a regulator or head-sluice. The supply is drawn into the canal at Myapur, and any surplus which the Hurdwar supply channel may bring down is thrown back into the Ganges over the Hurdwar and Myapur dams.



HEAD OF THE GANGES CANAL AT HURDWAR.

The works which control the supply of the Ganges canal are partly permanent and partly temporary. The Chillawalla weir, which is the one highest up the river, is now a permanent work; it was built originally of cribs and boulders to stop the retrogression of levels which was going on in the channel in which it is built, for it was feared that the river would forsake the right bank for the left one in a decided manner, and so render the supply of the Hurdwar channel very precarious. The Chillawallah weir has been made permanent with masonry which was laid on the foundation of the crib-work of the old weir. After the flood season is over, this weir completely stops the discharge down the channel which it spans. The next permanent work is the Hurdwar weir, or escape: this was built in 1872 across an opening opposite Hurdwar which had enlarged considerably since the canal was opened. This weir is a low one, with 110 shutters on the crest, 3 feet 6 inches high and 6 feet long; it is not generally used as the main regulator, but is employed when the surplus water cannot be conveniently discharged over the Myapur dam, which consists of seven vents of 20 feet, twelve of 10 feet, and ten of 5 feet, at different levels.

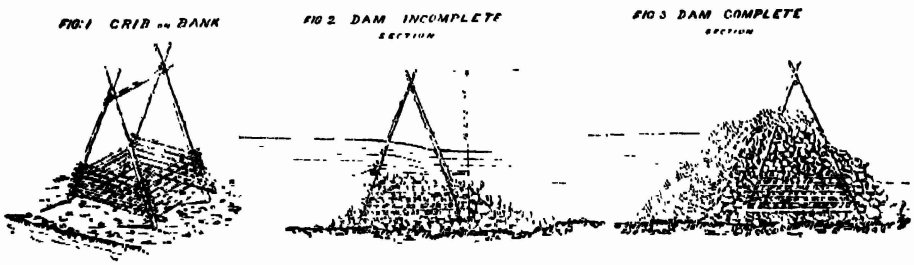
During the months of December and January the Ganges is at its lowest; the discharge then is generally about 5000 cubic feet, and may be as little as 3800 cubic feet a second. The river generally begins to rise during the first week in May, when the snows of the Himalayas begin to melt, and during the months of May or June all temporary bunds across the river are swept away; they crumble away like sugar

under the force of the current, and have to be reconstructed in the following September and October, when the river has fallen. They are usually completed about the 15th to the 20th November. When the river is low the entire discharge of it is compelled by the Chilla-wallah weir to flow on the right bank in the channel where the temporary dams are shown in the sketch. That channel is closed by three temporary dams, one behind the other. There is a considerable amount of leakage through the upper ones. The leakage from No. 1 is partially stopped by No. 2, and the leakage from No. 2 is almost entirely stopped by No. 3. Each dam is smaller than the one above it. In this way the entire discharge of the river is forced into the Hurdwar channel, and as in the month of November the discharge is usually much more than is required for the canal, the surplus is passed back into the river through the two dams or escapes, which have already been mentioned.

The construction of these temporary dams is a work of some magnitude in a stream having a surface slope of 10 feet or more in the mile, and in water which, in the case of No. 1 dam at any rate, is from 10 to 20 feet in depth. No. 2 dam is always less difficult to make than No. 1; sometimes it has to be made with cribs, but generally it is only an embankment of boulders and shingle. No. 3 is always a shingle dam. A number of cribs are first made on the foreshore of the river,* these are each about 10 feet in length, Fig. 1, and they vary in bottom width according to their vertical height, which has to be adjusted to the depth of the stream in which they are to be placed. The first operation in the actual construction of the dam is to get a 14-inch coir rope across the river. This is done by the help of ropes of different sizes, which are pulled across one after the other until one of sufficient strength is available to deal with the heavy rope. When the 14-inch rope is across the stream it is propped up, 20 to 25 feet above the water, at various points on groups of piles standing on the river bed, and between these supports it hangs down to within 8 or 10 feet of the water, the ends of it being firmly lashed on shore. Snatch blocks are run on each bight of the 14-inch ropes, which can be manipulated backwards and forwards on the rope by small windlasses on either bank. To these snatch blocks, ropes are fastened, to which boats can be attached, so that a boat can be pulled backwards or forwards, and placed at any point of the river. A barge, fitted with a derrick in the stern, first picks up one of the cribs which hangs over the stern of the boat in the water, the weight of it is counter-balanced by a quantity of boulders which is placed in

* 'Roorkee Professional Papers,' 2nd series, No. cclii. vol. vii.

the bow, the boat is then attached to a snatch block, and is pulled into the required position in the river. When the crib hangs in its right position in the line of the dam it is gradually lowered by the derrick into the water, and the boulders are taken from the bow of the derrick barge and dropped into the crib as it descends; other smaller



CRIBS USED IN CONSTRUCTION OF TEMPORARY DAMS, GANGES CANAL HEAD-WORKS.

boats are also dropped alongside, from which other boulders are placed in the crib sufficient to sink it to the bottom. When it is settled into its proper position it is firmly lashed to the neighbouring crib, which has been sunk before it, and a few more boulders, making a total depth of 3 or 4 feet perhaps, are filled into it so as to make it secure. The derrick boat is then pulled back to the shore by means of the snatch block running on the 14-inch rope, where it picks up another crib, which is sunk in the same way next to the last one and secured to it. In this way a line of cribs is placed right across the river or across the deeper part of it where the velocity is too great to enable a dam of boulders alone to be made. The water runs over the top of the boulders in the cribs, as shown in Fig. 2, and the dam is a submerged weir. The dam is then raised, foot by foot, by boulders which are dropped into the cribs from boats which are first pulled out one after another, by means of the snatch blocks, and the dam gradually rises up to the surface of the water; the crest of the dam is kept as near as may be at a uniform level, so that the water flows evenly over the top of it. When the crest is above water there is, of course, copious leakage through the boulder dam. At this stage grass *tattees* or mattrasses made of long bundles of grass, or thin twigs 6 or 8 inches in diameter lashed together by ropes, are placed in front of the dam as shown in Fig. 3. A pole or bullah is lashed to the lower edge of this mattress, and, behind this, boulders are placed on the mattress until it is sunk into position: it is important to allow the mattress to rest for a width of about 10 feet on the river bed, as this is the point where the greatest amount of leakage appears to occur. On

the top of this mattress a berm of small boulders and shingle is thrown, by labourers walking along the crest of the dam, until it has been made as strong and as staunch as is considered necessary. There is always a stream flowing along the face of No. 1 dam, and the consistency of the shingle berm depends on the velocity of this stream. No. 2 dam is also constructed in the same manner, or a portion of it, but No. 3 is a boulder and shingle dam, no cribs being necessary. As the current in front of these lower dams is much less than that above No. 1, they can be made of finer material, and therefore are more watertight.

CHAPTER IX.

HEAD-WORKS IN CLAY AND COARSE SAND.

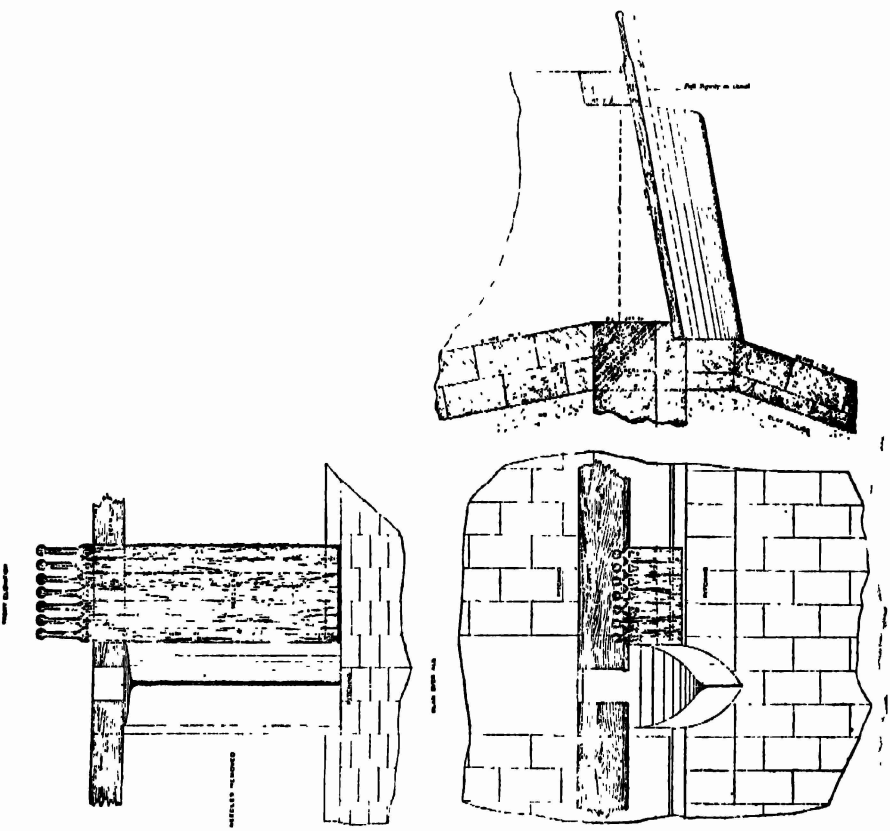
Sidhnai Canal Weir on the Ravi River—Weirs on the Mahanuddee in Orissa—Centre Sluice of Mahanuddee Weir—Mahanuddee Undersluices—Breach in the Mahanuddee Weir Weirs in deep Sand—Kistna Weir in Madras—Godaveri Weir—Coleroon Weir The Sone Weir in Bengal—Under-sluices of the Sone Weir—Sirhind Canal Weir across the Sutlej.

AN example of a weir of Class IV.* is found in the needle dam across the Ravi river at the head of the Sidhnai Canal near Multan, in the Punjab, where the slope of the river-bed is 0·083 per thousand (about 5 inches a mile) and the velocity of the stream in floods is only about 2⅓ feet a second. The discharge of the Ravi at this point rarely exceeds 12,000 cubic feet a second in floods, so the weir is a small one. A cross section of the river, on the line selected for the weir, showed that there was a good clay foundation for a length of 200 to 250 feet on each side at a reasonable depth below the level fixed for the crest of the weir, but that in the centre of the river the clay gradually sank to 40 and 45 feet below the level of the crest. To carry the foundations down through the sand to this depth would have been very costly, but, as the supply of the river ran very low at certain times of the year it was desirable to make the weir as watertight as possible, so that the entire discharge might be utilised in the canal. The bed of the river overlying the clay is sand. The weir has been constructed as shown in Plate XXXV.: when the clay was at a greater depth than reduced level 440·00 (the crest of the weir being 453·50) a trench was excavated in the sand to 440·00, and, below that level, sheet piling was driven in two lines 20 feet apart parallel to the centre of the dam, with cross lines 7 feet apart, at intervals of 23 feet, to act as boxing for pier foundations. These piles prevent the excessive percolation through the sand below, which would have been caused by the considerable difference in level, which exists in the dry season, between the water above and below the weir. As soon as the

* See page 111.

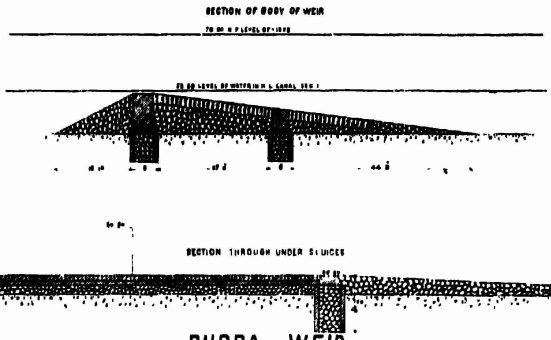
piles were driven, the foundations of the piers and body wall were built in concrete, and the trench was filled up with clay, the surface being pitched with brick blocks (2 feet by 12 inches by 10 inches), with a slope of 1 in 3 on the upstream, and 1 in 10 on the downstream face. The crest level of the weir (453·50) is 1 foot below the bed level of the canal, and is also below the general level of the sand of the river-bed, so the weir is practically all below ground except the piers which are constructed right across the weir at intervals of 20 feet in the clear. The weir is consequently not subjected to any scouring action of importance. The low surface slope, small depth, and small velocity of the floods rendered the construction of this simple weir possible.

The entire length of the weir is 737 feet. Between the piers timber beams are fixed, and the openings are closed by vertical needles of deodar wood, $7\frac{1}{2}$ feet long by 5 inches by $3\frac{1}{2}$ inches with a handle 18 inches long above, as shown in the following sketch :—



NEEDLE WEIR ACROSS THE RAVI RIVER, SIDHNAI CANAL.

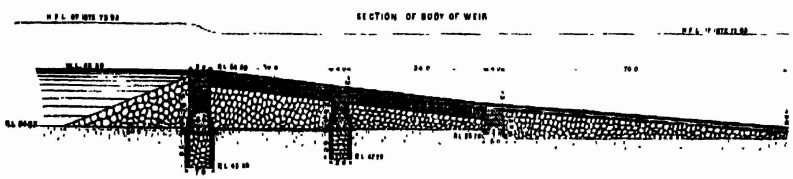
BRAHMINI WEIR

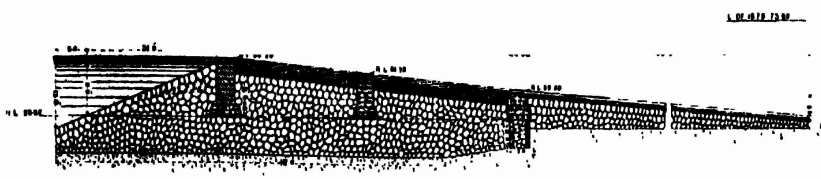


BURRA WEIR

BAITURNEE WEIR

MAHANADI WEIR





This weir has no under-sluices on account of the low level of the crest. It has been proved to be most efficient. The needles are easily manipulated and made watertight.

Plate XXXVI. shows cross sections of different portions of several weirs constructed in connection with the irrigation system in the delta of the Mahanuddee river in Orissa. The beds of the streams are generally in deep sand, but in some cases stiff clay, and in others laterite rock, which underlies the sand, rises to the surface. The object of the Mahanuddee weir was to raise the water of the river during the dry weather to a sufficient height to give a depth of 8 feet in the canals: this was accomplished by the construction of a weir with folding shutters 3 feet high on its crest. The total length of the weir is 6400 feet and it is calculated to discharge about 900,000 cubic feet per second in high flood; its crest is 64·50 above mean sea-level, or 13 feet above the average summer water-level of the river.

The weir is provided with two sets of scouring sluices, one in the centre and one at its southern extremity; the former divides the work into two parts. The portion of the work north of the centre sluices is 2950 feet in length, and is composed of a breast wall 12½ feet in height, 7 and 8 feet wide at bottom, and 4½ feet at crest, founded on wells from 7 to 9 feet in depth, with the exception of a length of 826 feet, which is founded on clay. At a distance of 30 feet from the breast-wall there is a second wall parallel to it, 5 feet wide at bottom and 4 at crest, and of a height corresponding to the rear slope of the weir, which is 10 to 1; it is founded in the same manner as the breast-wall: the interval between these walls is solidly packed with large picked rubble stone, each stone being about 2 to 2½ cubic feet; the lower wall is protected by a rough stone apron in continuation of the slope of 10 to 1, and was originally made 55 feet wide at its narrowest part, but additions have been made to this width from time to time.

The southern portion of the weir is 2600 feet in length, and constructed in the same manner as the northern part, with an addition of a third parallel wall at a distance of 34 feet from the second one: the same kind of rough stone apron as in the northern portion protects this third wall. The two first walls are founded partly on wells and partly on stiff clay. The third wall is founded on rubble stone.

The face of the weir along its whole length is protected by rubble stone packing, with a base varying from 20 to 40 feet.

The centre sluice is divided into ten bays, each 45 feet in width and 500 feet in all, including piers: each bay is provided with double wooden

shutters (see Plate XLIX., page 170): the flooring is of cut laterite and rubble masonry 4 feet in thickness, 115 in length, and 150 in breadth; and this is further protected by a rough stone apron 600 feet in length and 4 to 6 feet in thickness, divided into four parts by three parallel walls to prevent the packing from being carried away by the velocity of the current. Above the sluices there is also a rough stone apron about 30 feet in length and 600 in width, and from 4 to 5 feet in thickness. The sluice is connected with the body of the weir by flank walls. The whole of the work with the exception of the lower apron wall is founded on wells in sand.

The under-sluices (Plate XXXVII.) consist of 38 vents, each 5 feet in width, giving a clear waterway of 190 feet. The total length of sluice from flank wall to abutment is 344 feet: the length of the flooring is 115 feet of cut laterite and rubble masonry 4 feet in thickness, supported by a rough stone apron 110 feet in length, from $1\frac{1}{2}$ to 6 feet in thickness, divided into three parts by two parallel apron walls: there is a similar protection upstream, 30 feet in length. The piers and curtain walls were built partly on wells and partly on clay; the abutment and wing walls on stiff blue clay; the flank wall connecting the sluice with the weir was founded entirely on wells.

A breach occurred in the centre of the Mahanuddee weir in 1886, at the site of the centre sluices; about half the centre sluices were carried away, besides a portion of the weir, and a deep hole was scoured out on the line of the weir and below it. The cause of this failure was never satisfactorily explained, but it is supposed that leakage occurred, below the floor of the under-sluices, between the wells in its foundation, and that a stream was created below the floor which gradually undermined it. When a strain was thrown on the floor, during the early part of the flood season, it collapsed, and a breach 300 or 400 feet in width was soon scoured out by the current. The repairs of this breach, which took two years to complete thoroughly, cost about 250,000 rupees.

Plate XXXVIII. shows the head-works and weir at Panchkoorah on the Midnapore Canal in Bengal, where the nature of the foundation is very similar to that in Orissa. The under-sluices are fitted with gates similar to the Orissa ones.

Weirs of the fifth class, that is those founded on hard sand of great depth, are more numerous in India than those of the other classes. Pure sand, next to rock itself, is the best foundation that a weir can have. It is hard, it is indestructible, it is incompressible. But there is this danger in a sand foundation: the sand is liable to be disturbed

and carried away by running water. If sufficient protection can be afforded against any flow of water underneath the weir and against any excessive velocity over the bed of the river below it, the structure will stand secure. If materials are available, it is, in every case, only a question of time and money to make a weir across a bed of pure sand a certainty. The size of the stone used must be proportional to the velocity of the current: if only comparatively small stones are available the talus of the weir must be prolonged, so that by decreasing the slope at which the pitching stands, it may have the less tendency to be displaced. The velocity of the water passing over a weir is greatest at the crest: it is at this point that the heaviest stones are required in a weir of dry stone. Usually the crest is laid in masonry, in that case if the work be thoroughly well done large stones are not essential, provided that the mortar itself is sufficiently good to stand the erosion. Thoroughly well-laid rubble masonry, or even boulder* masonry, will often stand successfully where ashlar masonry has failed.

The weir across the river Kistna in Madras (Plates XXXIX. and XL.) claims first attention as one of the most remarkable of this class. It was built in 1854–55. The body of the weir itself is about 3000 feet long, but the entire length of the weir including the under-sluices and piers is nearly 4000 feet. The crest of the weir is 16 feet above the summer level of the river, and from 20 to 25 feet above the deepest parts of the original bed as it was before the weir was constructed. The river Kistna above and below the site of the weir is from $1\frac{1}{4}$ to $1\frac{1}{2}$ miles in width, but it narrows at the point where the weir is built to the dimensions given. A spur of sandstone runs down to the bank of the river at each side of the weir. The fall of the bed of the river above the weir is about 13 inches a mile, below it the slope is about 11 inches a mile. The ordinary greatest rise of the river in this gorge before the weir was built was 35 feet, and in extraordinary freshes as much as 38 feet has been recorded. The velocity of the river in freshes was as great as ten feet a second before the construction of the weir; the velocity over it now is said to attain 16 feet a second, at which times there is a depth of as much as 20 feet over the crest.

The construction of a weir at this point was a bold enterprise, but it was successfully accomplished. The bed of the river was very uneven on the line of the weir; the floods scoured out deep holes, sometimes on one side of the river, sometimes on the other. It was at one time intended to have filled up all the inequalities of the bed with stone,

* See pages 121 and 151.

but sand was used for this purpose instead. On the bank of sand, thus thrown up in the deep parts of the river, wells were sunk to a depth of 7 feet below the summer level. On the top of the wells a heavy course of ashlar masonry 3 feet thick was laid. Above this a massive wall of rubble masonry, 13½ feet high, 12 feet base, and 6 feet top, coped with ashlar, was built. Behind this wall a mass of rough stone of all sizes up to five and even six tons in weight was deposited. At 100 feet back from the main wall another one was constructed, the top of this was six feet below the crest of the weir; between the two walls the surface of the weir is packed with the largest stones placed on end, the interstices of these stones are filled as far as possible by quarry shivers jammed well into them. Behind this second wall the apron of the weir is continued for about another 100 feet with large stones.

This weir obstructs from three-sevenths to one-half of the former waterway of the river at the site where it is built, and although the action the weir is consequently great, very little repairs have been needed since the work was first completed in 1855. Some stone has been added year by year, and, on one occasion, a short length of the body wall was torn away. The yearly repairs have averaged about 1½ per cent. on the original cost.

The weir across the Godaveri river at the head of its delta on the Madras coast (Plate XXXIX.) was constructed some years before the weir on the Kistna: although it has in no part the large dimensions of that weir, it is one of the most remarkable in India. At the time when this work was undertaken, there was no weir in existence across a river of the width and capacity of the Godaveri. This river issues from the hills at a distance of about 60 miles from the sea; between that point and the coast the fall of its bed is very irregular, it varies from 3 feet to as little as 4½ inches in a mile, the average fall being between 5 inches and 6 inches. The rise of the floods at the point where the river issues into the plains is as much as 38 feet, and at the site of the weir the rise is 27 feet or 28 feet. The bed of the river is of pure sand. The Godaveri weir is built in four sections, the united length of which is nearly 12,000 feet; three islands in the bed of the river divide these sections from each other. Across these islands earthen embankments are constructed aggregating more than 6000 feet in length. These connect the four separate portions of the weir.

Plate XXXIX. shows the cross-section of the first and second lengths of the weir: the other lengths are very similar in design. The original idea for the weir contemplated a vertical drop wall with an ashlar floor

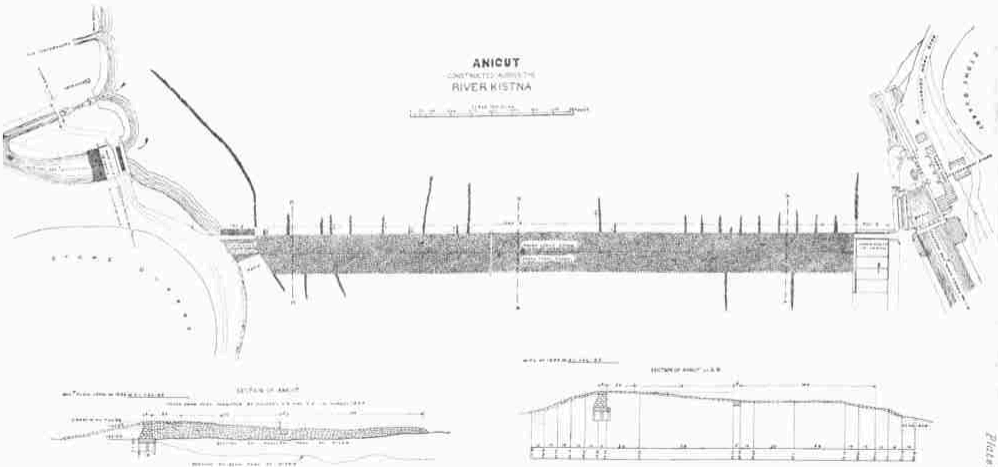


Plate XI

below, but this design was abandoned in favour of that shown in consequence of the difficulty in obtaining skilled workmen to execute it. The main wall of the weir is founded on circular wells which are 6 feet in diameter, and are sunk 6 feet in the bed of the river. The main wall itself is only 4 feet thick at the base, and 3 feet at the top. Over this there is a solid masonry flooring, 47 feet in width, of which 19 feet are horizontal, and 28 feet sloping, and slightly curved in section. This floor terminates in another row of wells similar to those under the main wall. The masonry floor consists of 4 feet of masonry covered with cut stone strongly clamped together. Below the lower row of wells there is an apron of rough stone pitching which varies in width, but is generally about 70 feet or 80 feet. The body of the weir between the two rows of wells rests on a core of sand which was thrown into place, wetted and rammed. The second section of the weir is very similar to the first, with the exception that the front wall is founded on a mass of rough stone which extends under the body of the weir in the place occupied by sand in the first section. The apron is strengthened by a bar of masonry, 4 feet by 3 feet, which is carried longitudinally through the length of this section of the weir. The third and fourth sections are generally similar to the first one, but the fourth section is rather stronger, the masonry is a few inches thicker, and the front slope is protected by a rough stone apron about 6 feet or 7 feet wide, which is carried along its entire length.

Another Madras weir, earlier in date than those which have been described, claims notice both on account of the fact that it was the first weir of considerable dimensions which was constructed in India by English engineers, and also because it shows how light a structure can be built across the bed of a sandy river. The weir across the Coleroon river in the Tanjore district was built in 1836, with the object of regulating the relative discharges of the Coleroon and Cauvery rivers, which bifurcate at the site of it (see Plate XLI.). The Coleroon river is 2250 feet broad at this point; the fall of the bed is about 3½ feet per mile. The freshes rise about 15 feet above the summer level of the river; the bed is of pure sand. As it was originally built the weir consisted simply of a rectangular bar of masonry stretching across the river bed. This bar was founded, on the upstream side, on a double line of wells sunk 6 feet into the sandy bed of the river, and, on the downstream side, by a single line of similar wells. Above these was a masonry floor 27 feet broad by only 3 feet thick, 2 feet of this being brick masonry; and the upper foot, below the weir wall, was ashlar masonry carefully laid.

The weir wall itself was rectangular in section; it was 6 feet broad throughout and 7 feet 4 inches high in the northern section of the weir, and 5 feet 4 inches in the two other portions; the weir was divided by two small islands into three separate lengths. Below this bar of masonry there was a rough stone apron only 9 to 12 feet broad by 4 feet deep. The weir wall was cut through by twenty-two sluices 2 feet broad by 3 feet 6 inches high; these were placed at intervals along the weir.

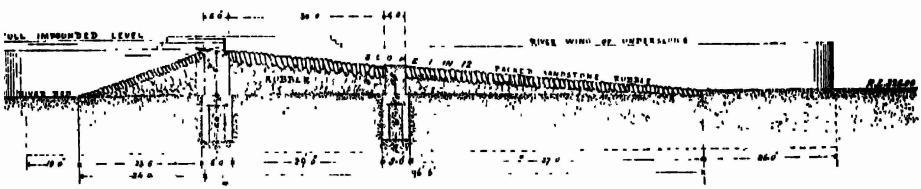
This structure was an extremely light one, especially as regards the width and thickness of the floor and of the pitching below it. An accident did occur to the weir the season after it was completed, a length of about 240 feet of it was swept away. This accident was caused by the leakage of water below the weir wall, which undermined the foundations; the water, before the weir gave way, could be seen bubbling up in many places through the apron below the weir whenever there was a head of 5 or 6 feet of water on it. The weir was repaired immediately after this accident and was materially strengthened, and from time to time the rough stone apron has been increased as occasion demanded; but it has been proved that the design of this weir, weak as it is, is a sufficiently strong one in this particular case. Several alterations have been made to the weir since it was built, the level of the crest has been lowered and the width of the apron has been increased in parts of the work. A masonry foot bridge has also been constructed over the entire length of the weir, and the sluices have been remodelled. Typical sections of it are given in Plate XXXIX.

The head-works of the Sone canals in the district of Behar in Bengal are shown in Plate XLII. The bed of the river is deep sand with occasional layers of small pebbles. The river has its source in the plateau of Central India,* and joins the Ganges near Patna after a course of 325 miles, mostly through the rocky region at the base of the Kymore Hills. After it leaves the hills, the river, in the last 100 miles or so of its course, assumes a deltaic character, which is very marked in the immediate vicinity of the Ganges. The drainage area of the river is about 23,000 square miles, its maximum discharge is 830,000 cubic feet a second, and the minimum in the hot weather has fallen to 450 cubic feet. The maximum rise in the river flood at the site of the head-works is 15 feet above the summer level. The fall in the bed of the river after it emerges from the hills gradually decreases from 2·7 feet to 1·7 feet in the mile, and the width and cross section of the river decrease in the lower reaches near the Ganges. The head-works are situated at Dehree,

* See Frontispiece.

about 25 miles below the point where the river leaves the hilly ground and about 40 miles above the point where it spills over its banks on occasions of high floods.

The weir across the Sone is believed to be the longest in one unbroken piece of masonry which has been constructed, the length between abutments is 12,469 feet. The weir consists of two parallel walls 30 feet apart, founded on rectangular wells 10 feet by 6 feet, sunk 10 feet below the original bed-level and filled with concrete: between these walls the weir is hand-packed with large rubble stone at a slope of 1 in 12, and this packing is continued below the lower wall at the same slope down to the bed of the river. The upstream slope above the upper wall is smaller rubble packed at a slope of 1 in 3. About 2000 feet below the weir is the Sone causeway, which was constructed



SECTION OF THE SONE WEIR, 12,469 FEET LONG.

long before the weir as a portion of the grand trunk road which crosses the river at this point: it is now a continuous piece of masonry right across the river. There is no probability of any retrogression of levels in the bed of the river below the weir; but, if there were any danger of this, the causeway might easily be made a powerful defence to the weir. The weir is pierced by three sets of scouring sluices. There is one set of 16 vents of 20 feet 7 inches in the centre, and one set on each flank consisting of 20 vents of 20 feet 7 inches, just below the head-sluices of the canals.

The original level of the river bed was about 326·00; the crest of the weir is 334·00, or 8 feet above the original bed. The under-sluice and the centre sluice floors are at 326·00 (but immediately between the piers there is a short length 9 inches higher between the shutters) and the tops of the under-sluice piers are 336·00. The highest flood is rather more than 8 feet above the weir crest. The weir obstructs about one-half of the former waterway of the river, but the afflux has been calculated to be only about 15 inches; there is no spill over the banks above the weir, and there are no marginal embankments nor protective works of any kind. The banks of the river are of hard soil with some

kunker* mixed with it. The floor of the head-sluices on each bank of the river is 326·00, the same as the under-sluice floor, or 9 inches below the step in the under-sluice floor between the shutters. It would probably have been better if the under-sluices had been sunk deeper, as the amount of sand and silt which is carried into the canal is excessive (Chap. III., p. 39), although the head-sluice gates are divided into two parts.

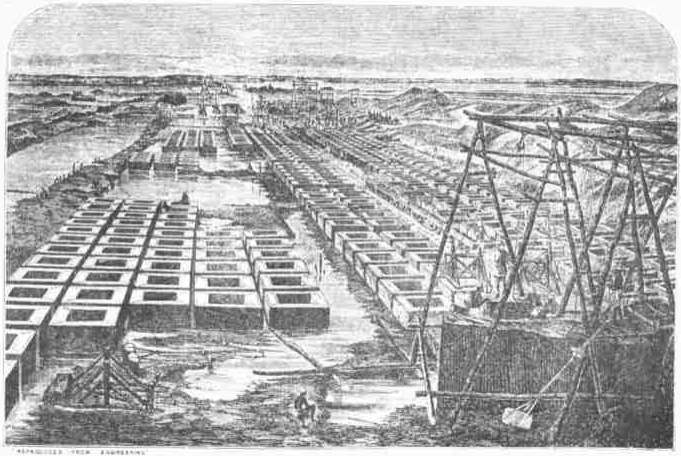
Before the weir was constructed objection was taken to the design on the ground that the wells in the substructure,† except in the under-sluices, were of no use, and that as a weir with a long talus is intended to resist the action of the water on the surface of the river bed where the fall takes place, there was no necessity to have deep foundation, the theory of which is that the action on the bed is permitted, and the danger of a breach in the weir is guarded against by carrying foundations down to a depth where they will not be disturbed. This view is no doubt a sound one in cases where the river bed is impervious to the flow of water below the weir, but it ignores the consideration that, where there is any danger of such flow, a line of wells acts as a bar to underground currents and prevents the under-scouring of the structure.

The set of scouring sluices in the centre of the Sŏne weir were also the subject of criticism; it was said that they were far too limited in extent to affect the general deposit of sand above the weir to any appreciable degree. This view has been proved to be correct; the greater portion of the river bed above the weir has silted up to the level of the crest of it, and above it, and the centre sluices are only useful in so far that in a rising flood the discharge through them helps to fill up the river channel below the weir more quickly, and so reduces the action of the flood on the weir itself. The under-sluices on either flank have always maintained a good channel in front of the head-sluices.

The crest of the weir is fitted throughout its entire length with small iron shutters. Each shutter is 18 feet long by 2 feet 3 inches high, of light plate-iron stiffened with angle-irons. The shutters are hinged to tie-rods 4 feet long, which are capable of oscillating at their up-stream end on a horizontal pin attached by a rag-bolt to the crest of the weir. The point at which the tie-rods are hinged to the shutters is about 3 inches below the centre of pressure of the water when level with the top of the shutters; the shutters are, therefore, on the point of overturning when the water is at that level, and will overturn and fall into the

* Nodular limestone.

† Memorandum by the Inspector-General of Irrigation, dated 1st November, 1867.



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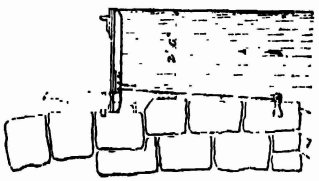
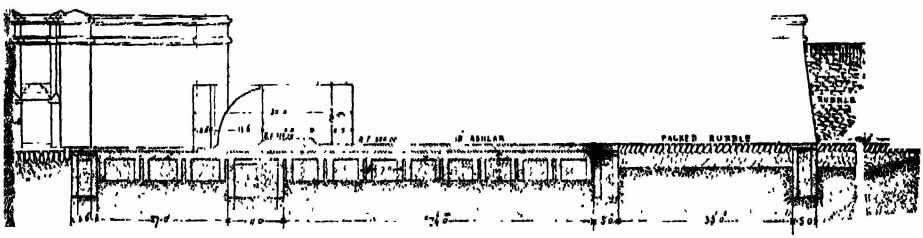
recess provided for them when the water rises higher. They will remain in that position all the flood season, and are raised after the floods by hand. Four men can raise these shutters, when a depth of 6 inches or 8 inches of water is flowing over the crest of the weir, almost as quickly as they can walk.



SHUTTERS ERECTED ALONG THE CREST OF THE SONE WEIR.

The shutters of the under-sluices are unique: they consist first of an upper shutter 20 feet 7 inches long, by 10 feet in height, hinged to the floor at its lower edge, and fitted with hydraulic brakes behind; and secondly of a lower shutter which is hinged to the floor by connecting-rods. The upper shutter is used to close the vents, and the lower one is used to retain the water and to open the vents; a detailed description of these gates is given in Chapter XI.

The under-sluice piers and the entire floor of the under-sluices, which is 537 feet by 123 feet, are founded on rectangular blocks or wells generally 8 feet square, Plate XLIII., which are sunk all over the entire area to a depth of about 8 feet: the blocks under the piers are longer and deeper. The wells are filled with concrete and covered with masonry topped with ashlar 18 inches thick. The under-sluice piers are not carried above high flood level, but are entirely submerged in flood; the crest of the pier is only 336·00, a high flood being over 324·00. The piers, which



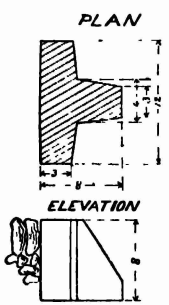
SECTION OF THE UNDER-SLUICES OF THE SONE WEIR.

are of ashlar, were at first built only 4½ feet thick, but this was found to be insufficient, as some of them were overthrown sideways in a heavy flood; they have now been reconstructed 6 feet thick, and strongly bound together by iron through bolts. The upsetting of the original piers was extraordinary, and has not been satisfactorily explained: five or six of them were upset together sideways, as though some force at right angles to the direction of the current had attacked them.

The Sirhind Canal in the Punjab is supplied from the Sutlej river at

Rupar. The bed of the river has a slope of about 2 feet a mile, and is composed of sand, with underlying shingle and boulders of moderate size. The minimum discharge of the river at this point is 2800 cubic feet and the maximum 133,000 cubic feet a second. The lowest summer level of the river is 857·8 above mean sea, and the highest flood, before the construction of the weir, was 873·35. The river commences to rise early in May, from the melting of the snows; the highest floods are at the end of July, by October the river has fallen to nearly its lowest levels. There are no great fluctuations between October and May; freshets are very frequent in July, August, and September. The highest flood on record rose 5½ feet in three hours, remained at full height for four hours, and then gradually subsided in ten days to the normal level of the river at the time. Plate XLIV. shows the head-works.

The under-sluices are at right angles to the stream, but the weir inclines up stream from the sluices at an angle of 15 degrees. The right flank of the weir consists of a revetment wall 350 feet long, the ends of which are set into the high cliffs which form that bank of the river. The weir proper is 2400 feet long: its crest was originally built at 865·00, or 8 feet above the general level of the river bed; but it has since been raised 1½ feet, and falling shutters, very similar to those on the Okla and Narora weirs (see page 154), have been erected along it. The weir consists of two walls, the upper one founded 7 feet and the lower one 3 feet below the ordinary river bed; the section of these walls is given in Plate XLV. The upstream slope of the weir is 1 in 3, and the lower slope 1 in 15. The under-sluice floor is 100 feet broad, 5 feet thick under the superstructure, and 4 feet elsewhere. The pitching below the floor is very heavy, each stone weighing as much as 30 cwt.: this pitching is partly laid in mortar. The under-sluices consist of 12 openings of 20 feet each, with draw-gates lifted by a winch travelling on rails above; both gates were originally 5 feet deep, but the upper one has been raised to 7½ feet. The under-sluice floor is 857·00, and the top of the gates 869·50, corresponding to the top of the falling shutter on the crest of the weir. At the toe of the stone pitching below the under-sluice floor, masonry blocks 12 feet by 8 feet are built as shown in the sketch. There was, at one time, some pooling downstream of the under-sluices to a depth of 20 feet below



PITCHING BLOCKS, SIRHIND CANAL.

the level of the river bed, but the slope of the pool from the toe of pitching was gentle, and there was no tendency to undermine the floor.

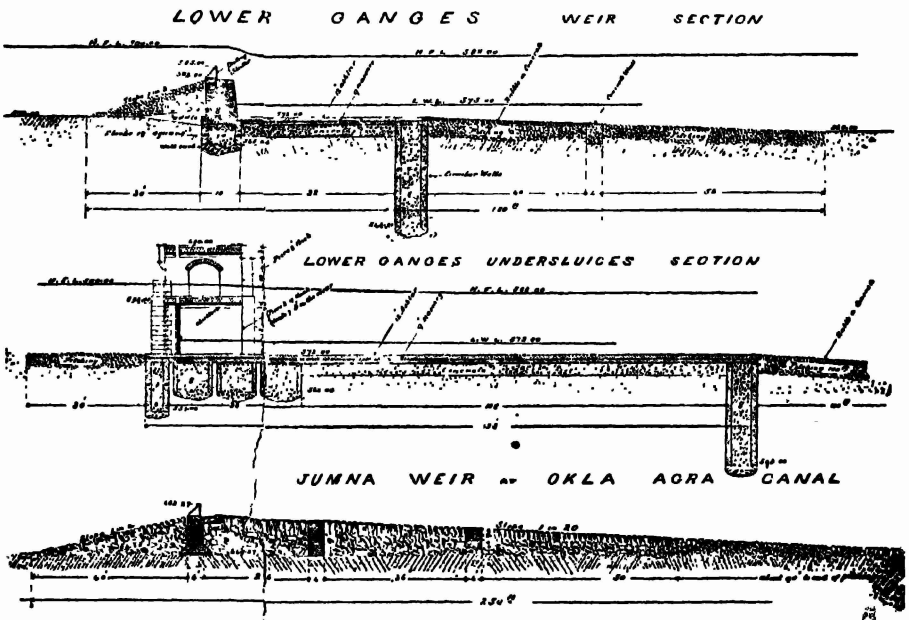
The ordinary supply in the canal is 3000 cubic feet a second, with 6 feet depth of water, and the maximum supply is 6000 cubic feet, with 9 feet of water. The head-sluice or regulating bridge (Plate XLV.) consists of 13 bridge spans of 21 feet each, divided into 3 sluice openings of 5 feet. The gates are of timber, raised by a traveller running on the parapet. A spear has occasionally to be used to depress the gates. The floor of the head-sluice is 2 feet above the under-sluice floor, and, in addition to this there is a board, sometimes 1 foot and sometimes 2 feet broad, in each vent, so that the supply can, under some circumstances, be drawn from above the gates, and not taken from the level of the floor of the sluice. The question of the silt in this canal is referred to on pages 43 to 45. There are double grooves in the piers, so that baulks can be placed, if necessary, in front of a damaged gate. Below the head-sluice the banks of the canal are revetted for some 500 or 600 feet.

CHAPTER X.

HEAD-WORKS IN FINE SAND AND SANDY MUD.

Weirs in Fine Micaceous Sand—Narora Weir across the Ganges—Protective Works above the Narora Weir—Narora Under-sluices—Under-sluice Gates of the Narora Weir—Head-sluice Lower Ganges Canal—Scouring Escape Lower Ganges Canal—Okla Weir of the Agra Canal—Under-sluices Okla Weir—Protective Works Okla Weir—Comparison of Deep and Shallow Foundations—Percolation below Weirs—Barrage across the Nile below Cairo—Reconstruction of the Nile Barrage—Cost of Indian Head-works.

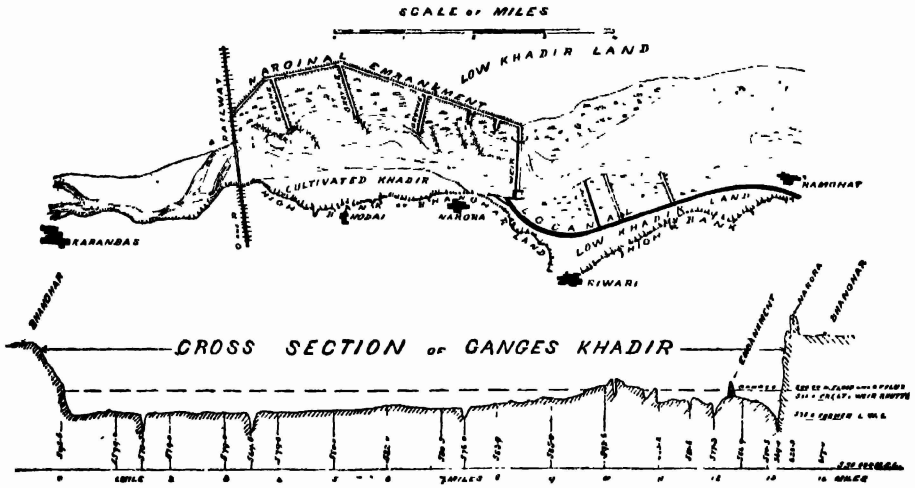
THE weirs which form the head-works of the Agra Canal and the Lower Ganges Canal are both constructed in micaceous sand almost as fine as flour. The Agra Canal weir is on the Jumna at Okla, and the Lower Ganges weir is on the Ganges at Narora. The following sketch shows the two weirs, which differ greatly in design :—



THE NARORA WEIR ON THE GANGES AND THE OKLA SECTIONS OF WEIR ON THE JUMNA RIVER.

The Okla weir is constructed on the surface of the river bed, with no foundations below that level, while the Narora weir has rectangular block and circular well foundations, which are sunk to depths varying from 7 feet to 30 feet below the river bed. The left bank of the Ganges at the site of the Narora weir is formed of very light friable soil, and the other bank is high and formed of red sand and clay: one bank of the Jumna at the Okla head-works is very light soil, but the other bank, where the Agra Canal takes off, is in rock. It was the existence of stone at Okla and the absence of all stone within any practicable distance of Narora which led to the difference in the two designs. The Okla weir is built of stone and the Narora weir of brick.

The following sketch shows the site of the weir at Narora across the Ganges:—



HEAD-WORKS, LOWER GANGES CANAL.

The weir obstructs about one-half of the waterway of the river, and the afflux caused by it is about 2 feet. The exceedingly friable nature of the soil on the left bank rendered it necessary to protect the weir against any erosion of the banks above it which might be caused by the increased height of the flood. The river immediately above the weir runs on its right bank close under the high land of the *bhangar*, which is chiefly composed of strong clay, but on the left bank the *khadir* land extends for some 12 or 14 miles before the high lands of the bhangar are again reached. The danger which was feared was that the river might cut into the low lands on the left bank, and possibly outflank the weir on that side: it was also necessary to protect the low

land on that bank from inundation. The river, when the head-works were commenced, had a course which was not nearly as straight on the weir as it now is: it ran in a tortuous course much nearer to the marginal embankment. One of the main objects of the training works was to force the main stream away from the left bank and to compel it to flow in a direct course from the railway bridge to the weir. Since the works were commenced there has been a constant struggle with the river, which is still kept up, to force it to flow along the right bank.* The protective and training works consist of a marginal embankment, 15 feet top, with front slope of 4 to 1, and rear slope of 2 to 1, which runs continuously on the left bank of the river from the railway bridge to the weir, and a series of groynes placed at right angles to the lateral embankment. The embankment was raised 3 feet above the calculated high water level, and was retired about 1000 feet from the wing of the weir in order to avoid erosion in high floods. The groynes are constructed with their crest level the same as that of the embankment at the point from which they spring. The groynes were made of the pure white sand of the river, which was the only material available, and for some time, especially during high winds, there was considerable difficulty in maintaining them. The heads of the groynes were strongly formed of double rows of piles driven into the bed of the river filled in with block kunkur.† The groynes were made gradually, year by year, and extended and altered from time to time according to the action of the river. These groynes were, and still are, supplemented by lines of spurs formed of trees, piles, and brushwood, such as are shown by the crossed lines in the sketch; these are constructed when the river is low, to check the velocity and to cause silt to deposit in the channel on the left bank. The result has been most successful, as the river is kept under perfect control, but the yearly maintenance of the training works is very expensive. Protective works are also necessary below the weir to defend the canal which runs in the low *khadir* land, which, below Narora, extends on the right as well as on the left bank of the river. The river at one time did cut in on the right bank below the weir towards the canal, but this action was stopped by groynes similar to those above the weir, which were thrown out to check the scour on the bank.

The Narora weir consists of a wall 8 feet thick at base and 10 feet high, founded on a line of blocks or wells 10 feet square and 18 inches thick, sunk 7 feet below the river bed. Below the wall is a horizontal

* 'Roorkee Professional Papers,' by Major H. H. Jones, R.E., vol. v

† A porous conglomerate of nodular limestone.

floor 40 feet wide and 5 feet thick, consisting of concrete 3 feet 3 inches thick, covered with a 9-inch course of brick masonry topped with 12 inches of ashlar. The wells at the toe of this floor are circular, 8 feet in diameter, and sunk from 20 to 30 feet in the sand. Below the floor is a talus 100 feet long, consisting of block kunkur pitching, the surface of the upper 40 feet being laid in concrete. The crest of the weir was originally built without the shutter which has now been erected continuously along it as shown in the sketch page 148. The crest was simply covered with ashlar 12 inches thick; these cover stones were thrown out of place in considerable lengths, the stones being lifted and thrown over the weir. The ashlar as it is now laid stands well, but it is laid with much coarser joints than the original work. It is a mistake in hydraulic work to attempt to deal with too fine joints; the result is that they do not get fully filled with mortar, and the water forces its way through them: coarse joints which can be thoroughly filled stand much better. This is shown in several cases: the floor of the Sone under-sluices and the floors of the falls or weirs in the Sone canals, which are covered with 15-inch ashlar, were, in the earlier years, frequently disturbed by the water working its way under the stones and lifting them bodily upwards: in several cases the floors of canal falls were found to be partially arched upwards when the canal was dried, and stones 5 feet by 2 feet by 15 inches were lifted bodily and removed 10 or 12 yards from their beds. This has now been cured by more careful bedding of the ashlar. The crests of the Ravi and Jumna weirs, which are laid in boulder masonry, stand well, although the individual stones are much lighter than those originally used in the Narora weir, and the upper Godaveri weir which consists of rubble masonry only has stood perfectly well: it is smoothed off with cement.

The shutters on the crest of the Lower Ganges weir are similar to those on the Jumna weir of the Agra Canal, they fold down on to the weir-crest in floods. They are rarely lifted or lowered more than once in the season, and no difficulty is found in manipulating them.

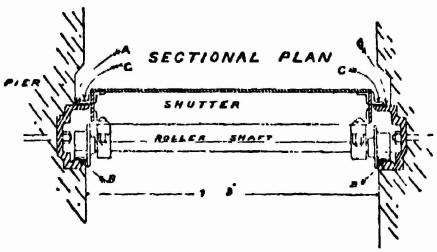
The under-sluices consist of 42 openings of 7 feet 3 inches each. These small openings are found to be sufficient to maintain a good channel in front of the head-sluice of the canal. The design of the under-sluices is peculiar. It consists of two tiers of arches between the piers. The lower tier of arches rises a little below high flood level, so that the floor above the arches is under water 4 or 5 feet in a high flood. The upper tier of arches makes a covered subway through which there is a passage from end to end of the under-sluices formed by arches in the

upper portions of the piers. This subway is very convenient to the men who have to manipulate the gates, and it is also useful for the repair of the shutters, as each one can be drawn up and deposited in the subway. The roadway above the upper tier of arches is 10 feet above the highest flood, and on this roadway a travelling crane runs, by which the shutters of the under-sluice are manipulated. The work is divided into three groups of shutters by piers 7 feet 3 inches thick, but the intermediate piers are only 2 feet 9 inches thick. The part of the foundation which lies under the piers and superstructure is entirely composed of masonry blocks 18 inches thick, which are sunk below the floor. The front row of blocks are each 11 feet long by 6 feet broad sunk 15 feet, and the three lower rows are 10 feet square sunk 10 feet; all the blocks are filled with concrete. The floor, which is 427 feet by 155 feet, is entirely surrounded by wells sunk to various depths, and also divided into three bays by wells sunk in the line of the thick piers. The floor is 5 feet thick, similar to the weir flooring. Below the floor is 100 feet of kunkur block pitching. Underlying the light sand of the river bed is a stratum of clay connected with the high bank on the right of the under-sluices; most of the blocks and wells in the under-sluice floor are sunk to the clay, and those blocks and wells in the weir proper, which are within 500 feet of the under-sluices, are sunk into the clay, with the object of securing the weir against the scour of the water issuing from the under-sluices. Altogether the structure is an exceedingly strong one.

The level of the under-sluice floor is 572·00 which is the same as the weir floor, the level of the weir crest is 582·00, and the top of the weir crest shutters is 585·00. The under-sluice shutters are 13 feet high, the top of the gates being 585·00. They are iron draw-gates lifted vertically in grooves by a travelling winch on the upper roadway which is at 600·00, the highest flood level above the weir being 590·00. The under-sluice gates can be lifted until the top of the gate is at the upper platform level (600·00) so that the lower edge of the gate is at 587·00, or 3 feet below the highest flood. The masonry platform over the lower arches is also below high flood level. It might be thought that it would have been better to have arranged so that the gates and lower arches would have been clear of the high flood, to avoid floating trees and brushwood, as has been done in the case of the Ravi, Sutlej, and other weirs, but no practical difficulty has ensued, as there appears to be but little floating debris in the river at this point.

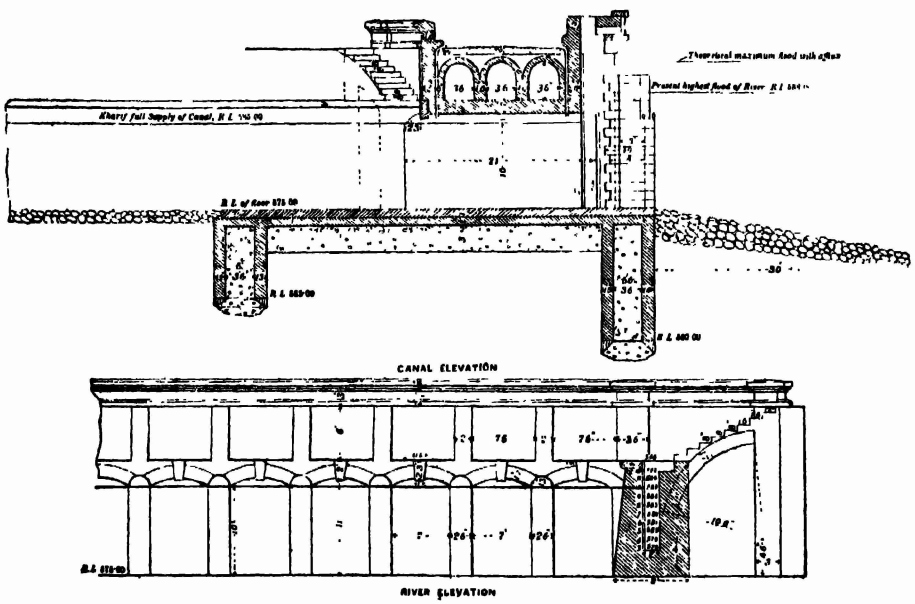
The under-sluice gates, which are of wrought iron, are unlike those in any other weir. Each gate is fitted with four pairs of rollers, which are

keyed to a wrought-iron shaft which is continuous across the gate. These rollers run in vertical cast-iron grooves, bolted to the piers, of the cross section shown in the sketch below. The paths B, on which the rollers run, are vertical; the flange A of the grooves is tapered slightly, and the angle-iron C which is riveted to the gate is set at a corresponding angle; when the gate falls vertically on the floor, guided by the rollers, the angle-iron C bears on the tapered face A, and staunches against it, the pressure being thus removed from the rollers to a great extent. As soon as the gate is lifted an inch or two from the floor, the rollers come into bearing and the friction on the face A ceases. The arrangement is a good one but expensive, and perhaps more elaborate than the occasion demands.



UNDER-SLUICE SHUTTERS, NARORA WEIR.

The section of the head-sluice is shown in the sketch below :—



HEAD-SLUICE OF LOWER GANGES CANAL AT NARORA.

The floor, it will be noticed, is at 575·00 or 3 feet above the under-sluice floor. The work is surrounded with blocks or wells sunk into the

sand, and the floor is divided by lines of blocks the same as the under-sluice floor. The foundation consists of concrete rammed into the compartments formed by the sunken blocks. The high level of the head-sluice floor as compared with that of the under-sluices is of advantage in excluding sand from the canal bed. The silt in the waters of the river is very fine sand mixed with a considerable proportion of earthy matter which is advantageous to the crops. The maximum velocity in the canal is rarely above 2½ feet a second, which is sufficient to carry forward a large proportion of the silt to the fields. A certain amount of silt is deposited in the first 2 miles of the canal, but it is not much, and no dredging at all is necessary. At the second mile of the canal there is a powerful escape (with 70 lineal feet of waterway down to the canal bed) by which the discharge of the canal can be returned to the river; the scour induced in the canal by this escape can be used to displace the greater portion of the silt deposited in the flood season. There is an ample supply of water in the river, the minimum discharge being about 3000 cubic feet a second.

The Okla weir is believed to have the greatest width in cross section of any weir in India. In parts it is as much as 250 feet from the toe of the upper pitching to that of the lower talus. There are first two longitudinal walls 30 feet apart from centre to centre * and 4 feet thick; the upper one is 10 feet and the lower one 9 feet high; the interval between them is filled with rubble stone and carefully packed with very large rubble on the top. There is a third wall 4 feet 9 inches high 40 feet below the second one, and the interval is packed in the same way. The rubble used in the packing is very large; there are occasional stones as much as 6 feet by 3 feet by 2½ feet, and all the stones are larger than those usually employed in such work. The weir was much damaged by the first floods which passed over it before it was completed in 1871, and large quantities of rubble had to be thrown in below the talus of the weir, and below the head-sluices, which were very nearly carried away, a hole some 50 feet deep being scoured out at the end of the floor. The velocity over the crest of the weir in this flood was 9·3 feet a second, but that over the talus where the damage was done was estimated to be over 18 feet a second at a point some 40 feet below the crest. The weir was at first constructed without any shutters on the crest, but it was found necessary to raise the level of the pool, and wooden shutters 3 feet high were erected as shown in the sketch on page 148. These are hinged by holding-down bolts to the weir at their

* 'Roorkee Papers,' by Major H. H. Jones, R.E., vol. iii. second series.

lower edge, and, when erected, are held up by chains in front of them, which are fitted with let-go gear. The floods in the river rise slowly, and it is easy for men to walk along the weir crest when the water begins to rise in flood, and to release the let-go gear ; the shutters then fall on the crest and remain down during the floods. When it is necessary to raise the level of the pool above the weir, men lift the shutters by hand and attach the chains.

The under-sluices of this weir consist of only sixteen vents of 6 feet each in width and 10 feet high ; the total length of the weir (including the under-sluices) is 2572 feet, and, for this length of weir, the ventage of the under-sluices is abnormally small. The crest of the weir is 659·27, the floor of the under-sluices being 648·27, and that of the head-sluice of the canal 652·27, or 4 feet above the under-sluice floor. On the right bank of the river, where the canal takes off, there is a rock foundation for the head-sluice, but the under-sluices are in sand. The foundation of these is surrounded by lines of blocks sunk to various depths from 9 to 20 feet, and hearted with concrete. Some of the wells in the left wing wall are sunk to nearly 40 feet. The floor of the under-sluice, which is of rubble masonry 4 feet thick covered with 2 feet of ashlar, is 72 feet broad on the line of the axis of the river, with heavy pitching below. The under-sluice vents are arched over the piers, the arches, as in the Narora weir, being below the high flood level. A high flood stands 17 feet on the under-sluice floor.

The head-works are protected on the left bank by an embankment, not dissimilar to that at Narora, which is connected with the weir and extends for seven miles above it. Groynes are thrown out at intervals from the embankment to check the velocity along the river face of it. In order to train the river it has been found necessary to construct permanent groynes with stone noses instead of tree spurs and sand bunds as was originally proposed : the yearly expenditure on the training works above the Okla weir averaged 43,000 rupees from 1886 to 1890, but it is expected that, now that the permanent works are complete, 10,000 will suffice in the future. The discharge of the river in high flood is only about 150,000 cubic feet a second; but the weir obstructs more than half the original waterway of the river, and the afflux is said to exceed 3 feet. The action on the weir slope is consequently very severe, even although the floods rise very slowly and fill up the reach below the weir before any severe strain is brought upon it.

There is not any large silt deposit in the canal and no dredgers are employed. There is an escape, with waterway rather greater than that

of the head-sluice, in the second mile of the canal, by which some portion of the silt can be scoured out. The silt is of a very fine nature. The maximum velocity in the canal is 2½ feet a second. The river bed above the weir has silted up to the level of the weir crest practically.

The Agra Canal weir at Okla is an example of what can be done in the way of constructing a weir without any depth of foundation, even in extremely friable soil, provided that there is ample heavy material available to resist the high velocity and great erosion in the lower slope, and provided also, and this point is of great importance, that the flow of the stream can be constantly maintained at right angles to the weir. Strong currents parallel to the face of light foundations are most disastrous. In this case it has to be borne in mind that the floods rise slowly, and there is less danger of any sudden alteration in the main currents. The stability of this weir has no doubt been greatly increased by the deposits of silt which have occurred above it, and which have tended greatly to prevent any probability of serious percolation immediately under the weir, which might undermine it. In cases where dangerous parallel currents are not likely to occur, a 6-inch deposit of silty mud in the channel of a river above a weir is a better security against underscour than foundations 50 feet deep. It has been maintained that, in those cases where the chief danger to a weir is from underscour and not from parallel currents, the true measure of the security of a weir in a permeable bed is the distance through the soil which a current of water would have to travel before it could rise up below the weir, and that it is of little consequence whether masonry is laid horizontally on the river bed or sunk vertically below it, so long as currents passing through the soil below the structure are exposed to the friction of the same length of passage. This view appears to be sound, but it is essential to attach to the application of the principle the conditions that the weir must be protected from longitudinal scour on the face and toe, that it must have sufficient weight to resist the horizontal pressure of the head it supports, and also sufficient weight to oppose the upward pressure on the base of the foundations which that head may produce; and, further, that the surface of it which is exposed to erosion, shall be of material sufficiently hard and sufficiently heavy to resist that erosion. For the mere purpose of making a weir watertight, and so saving water in the dry season for irrigation, deep foundations, if carried down to an impermeable stratum, are, of course, of great value; and in deep sandy beds they have a certain value, as they impede the amount of percolation below the weir to a certain extent, but their value in this respect is not

as great as may be supposed. If the bed of a river is in deep coarse sand the water will percolate through it below a weir from the higher to the lower level, in spite of foundations; and, if the bed of the river immediately above a weir has been staunched by silt deposits, the percolation, although checked, will still take place from a point higher up the river where the bed has not been so staunched, and, although the percolation may perhaps be reduced by deep foundations, it will not in such a case be stopped. This may be seen in several Indian weirs in deep sand. In the Sone weir, for instance, the silting above the weir has been very marked, and the weir itself is very fairly watertight; but in the dry season, when water is very valuable and when every effort is made to keep all the shutters in the weir as tight as possible, so that every available drop may be pressed into the canals, there is a considerable stream in the river two or three miles below the weir which is formed of water which has percolated through the deep sand on which the weir is founded. The foundations in this case are 10 feet below the river bed, and it is questionable whether the amount of water which passes below this weir would have been affected if the foundations had been 30 feet deep, or, indeed, if the weir had been founded on the river bed instead of being depressed into it; but the depth of the foundation in this case has been fully justified as a protection against the possibility of dangerous parallel currents.

The principle of trusting to the width of base rather than to depth of foundation, which has been successfully adopted at Okla, finds an almost equally striking exemplification in the Barrage across the Nile below Cairo. This fine work, which is strictly speaking a regulating bridge, and not a weir, is founded on extremely friable soil, composed of alternate beds of fine river sand and alluvial mud of a finer and more soluble nature than that on which the Narora and Okla weirs are built. Borings which were made into it to a depth of 100 feet showed that the soil did not improve with the depth, and that it melted * almost like sugar when brought in contact with water.† The Barrage consists of two regulating bridges placed across the two deltaic branches of the Nile at the point where they bifurcate from the single stream of the river. The floors of these regulators are at the level of the river bed and the obstruction which the work offers to the floods of the river consists of the piers and the flank locks. The piers are 6·56 feet (2 metres) thick.

* 'Minutes of Proceedings of the Institution of Civil Engineers,' vol. lx. p. 374.

† 'Note on the Nile Barrage,' by Colonel Sir Colin C. Scott-Moncrieff, K.C.M.G., R.E., Cairo, 1890.

The vents between the piers are 16·4 feet (5 metres) in the clear, covered with arches which carry the roadway above. There are 61 spans in the Rosetta Barrage and 71 in the Damietta Barrage. The entire length of the Rosetta Barrage is 1525 feet (465 metres) and the Damietta Barrage 1765 feet (535 metres) including the flank locks. The total obstruction to the floods of the river is rather more than one-fourth of the original waterway. A portion of the work was founded upon a bank of rubble stone which was thrown up in one part, where the bed was below the general level, but generally the foundations were laid in the muddy bed itself. When the foundations came to be examined during the progress of the repair (or partial reconstruction) which was executed in 1886–90, it was found that this bank of rubble had become staunch, the interstices having become quite filled, apparently with silt deposits. The foundations of the Barrage were originally designed as shown in black in Plate XLVI.,* and were supposed to have been constructed in that manner with the addition of a sloping masonry talus 49 feet (15 metres) broad and $8\frac{3}{4}$ feet (2·66 metres) thick: but it is doubtful whether the floor below the superstructure really was built $12\frac{1}{3}$ feet (3·75 metres) thick as shown in the plate; and the talus, if it was constructed, was almost entirely swept away before 1886, as only traces of it could be found when the reconstruction of the floor was executed. The Barrage was commenced in 1843 and was first tried in 1863. The gates, which were of a very different pattern to those now in use, were fitted to the Rosetta Barrage, but none were erected on the Damietta side: the maximum head placed on the Rosetta Barrage was 5 feet 9 inches (1·75 metres) and that was only imposed for a short time. Ominous cracks soon appeared in the work, and serious settlement occurred: from 1867 until 1883, when the engineers appointed under the regime of the British occupation took charge of the irrigation works of Egypt, this grand work lay practically useless. It was never intended that the Barrage should be used during the flood season otherwise than as a bridge, but on the fall of the Nile, the intention was to use it as a regulator to maintain a certain level above it: in low Nile the maximum head was to have been 14 feet 9 inches ($4\frac{1}{2}$ metres) but the work leaked so badly and the cracks and settlement were considered so dangerous, that, as has been said, it was not considered safe to subject it to a strain of more than a fraction of the head it was supposed to be able to stand. In 1884 and 1885, the Barrage was tested in various ways: in the first

* Except that the heads of the piles projected above the floor, and the piles were consequently much shaken by the stream.

year the vents were partially closed, and a head of 7¼ feet (2·20 metres)* was placed on the Rosetta branch and about 3 feet on the Damietta branch Barrage, but in March 1885 more cracks appeared in the Rosetta branch and there was a subsidence of an old coffer dam put in years before to protect a doubtful part of the foundations. In 1885 a bar of rubble stone was thrown across the floor on the lower side, and the pressure was partly taken by the Barrage gates and partly by the stone dam which made a second drop in the water-level. In this way a head of 10 feet was obtained: but it was evident that these temporary expedients could not be continued, and in 1886 a decision was arrived at to repair or reconstruct the floor on the designs of Colonel Western, R.E. The object was to prevent the percolation which rendered the original work insecure: when the reconstruction was being carried out the springs, both through the original floor and under it, gave great trouble, and the problem was to so reconstruct the floor as to stop the passage of water through and under the work. Sir John Fowler some years before had proposed to sink a curtain wall 60 feet deep below the level of the original floor, but this plan was not adopted owing partly to the great expense, and partly because it was feared that in sinking the curtain the old foundations might be so disturbed that the existing work would be irreparably injured. The plan which was carried out was substantially that shown in red on Plate XLVI., but the actual width and thickness of the new work was varied in places, according to local circumstances and according to the quality of the work found in the old floor: in one place for instance the new floor laid on the top of the old one was increased from 4 feet to 10½ feet (3·25 metres) in thickness, and the lower floor, which is shown 15 metres broad in the plate, varied in width from 10 to 15 metres. Generally the reconstruction of the floor was as follows:†—The whole of the original floor of the Barrage was raised more than 4 feet (1·25 metre) with concrete in cement, faced (for a width of 23 feet under the gates) with Trieste ashlar, and above and below that, within the limits of the old floor, with Cairo ashlar. Beyond the old floor, on the upstream side, the new floor was extended to a width of 82 feet (25 metres) and 3¼ feet (1 metre) thick in rubble masonry in cement, a row of sheet piling‡ being driven 16½ feet deep below the floor at a point 16½ feet (5 metres) from its upstream edge. Downstream of

* 'Reports of the Egyptian Irrigation Branch for 1884 and 1885,' by Col. Sir C. C. Scott-Moncrieff, K.C.M.G.

† 'Barrage Repairs. Report of working season 1887,' by Mr. A. G. Reid, director of works.

‡ These piles were omitted in a portion of the work.

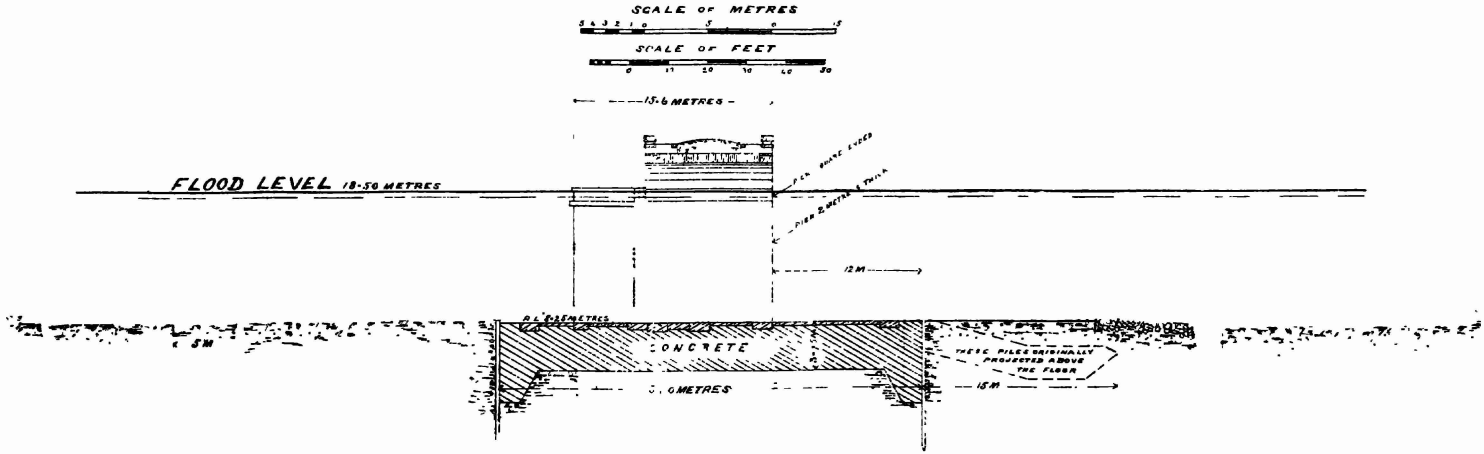
the original floor the new one was extended, also in rubble masonry in cement, to a width varying from 33 feet (10 metres) to 49 feet (15 metres) and 4 feet (1·25 metre) thick. So that practically an entirely new and impervious floor, from about 220 feet to 240 feet broad, was laid over, and extending both above and below, the old floor. In addition to this a width of about 43 feet (13 metres) of rubble pitching was laid above the upstream floor, and below the downstream floor a row of rubble masonry blocks about 16½ feet by 10 feet by 5 feet (5 metres by 3 metres by 1½ metre) was built at a distance of 16½ feet from the downstream edge of the floor, and the space between was filled with dry rubble pitching covered with a layer of rubble masonry blocks 8¼ feet square and 2½ feet thick. Beyond this outer line of blocks rubble pitching was laid in varying widths according to the bed of the river, so that the total width of the work, inclusive of block and rubble pitching, extends in some parts to more than 400 feet, the greatest width of the Narora and Okla weirs, which sustain a maximum head of 10 feet, being 250 feet. In the case of the Barrage, which is to sustain a maximum head of 13 feet, the width of the impermeable masonry floor is 220 to 240 feet, as compared with 155 feet in the Narora and 72 feet in the Agra weir under-sluices. In the Damietta branch ten of the arches at the west end were filled up, so the two branches now each consist of 61 openings.

The repairs or reconstruction of the barrage, including the new drawgates, which are similar to those in use in the canals of Upper India (see Plate LI.), have cost about 425,000*l*. The result has been successful, and very beneficial to Egypt. In 1890 a head of 10 feet was sustained without difficulty, which was increased in 1892 to 12½ feet; but the work is still a source of anxiety, and needs constant care and attention. In March 1891 the barrage across the Damietta branch showed signs of leakage * below the floor; a little eddy formed upstream, and violent bubblings, accompanied by a stream of water, appeared on the downstream side of the work. The pressure was reduced in this part, and as soon as possible the surface above the barrage in the vicinity of the leak was dredged out and replaced by fine clay or puddle. In 1892 the leakage was very small: during the hot weather the gates were made perfectly watertight by being caulked with rags, and the total amount of water which passed the barrage could have been taken up by a few small pumps. Some of the clay which had been laid to check the leakage has been scoured away by the floods, and it is

* 'Report of the Administration, &c., of Egypt,' 1892, Parliamentary Papers, p. 17.

CROSS SECTION OF THE BARRAGE OF THE NILE

BLACK AS ORIGINALLY BUILT



proposed to renew it, and cover it with a skin of concrete as a protection; it has also been proposed to bore holes through the floor and force cement mortar through them to form a sort of curtain wall by consolidating the soil below, but the former plan seems the better one.

Sir Colin Scott-Moncrieff says, "The moral is that while the barrage may be pronounced a sound reliable work, so long as it is carefully watched and repairs always effected as they are required, it would be madness to cease this careful surveillance."

COST OF INDIAN HEAD-WORKS.

	Maximum Discharge of the Canals.	Cost of the Head-works.
	cubic feet per second.	rupees.
Bengal:		
Orissa Canals	6,100	45,28,251
Midnapore Canal	1,400	5,20,633
Sone Canals	6,000	23,16,876
N.-W. Provinces:		
Ganges Canal *	6,800	3,28,920
Lower Ganges Canal	5,100	36,93,146
Agra Canal	1,500	11,69,619
Eastern Jumna Canal	2,350	17,00,757
Betwa Canal	1,200	9,63,469
Punjab:		
Western Jumna Canal	3,300	4,65,032
Bari Doab Canal	4,800	7,59,147
Sirhind Canal	6,000	12,10,806
Chenab Canal †	2,350	29,09,822
Sidhnai Canal	1,500	1,42,949
Madras: ‡		
Srivaikunthum Anicut System ..	1,860	2,33,120
Sangam Anicut System	4,800	7,18,240

* This canal has a temporary weir or dam constructed each year.

† These head-works are not completed; the figure given is the estimated cost.

‡ The correct figure for the older Madras Canals—the Godaveri, Kistna, Cauvery, and Penner—are not available.

The cost of the head-works of irrigation systems varies enormously according to the nature of the river in which they are constructed. The table on the previous page shows the actual cost (up to the end of 1890–91) of the head-works of the chief perennial canals of India. The figures show the cost of the works only, and do not include the charges for establishment, tools and plant, &c., which would increase the amounts by about 25 per cent.

CHAPTER XI.

GATES OF UNDER-SLUICES AND WASTE WEIRS. MOVABLE DAMS.

Principles of the Construction of River Weirs Central Sluices in a Weir of doubtful value—Size of Under-sluices—Baulks and Needles in Under-sluices—French Shutters in Orissa and Midnapore—Hydraulic Brake Shutters of Sone Weir—Fouracres' Double-tumbler Shutter—Movable Dam on the Ariah Canal—Under-sluice Gates in Upper India—Gates on the Barrage at Cairo—Under-sluice Gates of the Bhatghar Dam Automatic Waste Weir Gates—Gates of the Bhatghar Waste Weir, Bombay.

IN the foregoing chapters detailed descriptions of several under-sluices have been given. It is most difficult to lay down any general rules for the construction of these important adjuncts to a river weir, indeed it is doubtful whether there are any accepted principles to regulate the dimensions which it is desirable to give to under-sluices. The earlier examples* constructed in Madras, were made with vents about 6 feet broad, and raised to only about half the height of the flood, but recent practice has been to increase the width of the vents to 20 feet (or even more) and to make the openings clear above high flood. It is nearly always necessary to have a set of under-sluices below the offtake of a canal, to prevent the accumulation of silt immediately in front of the head-sluice: and it used to be held desirable to have an additional set in the centre of long weirs; it is now considered that central sluices are not of much practical value, and it is generally held to be better to maintain a channel across a river above a weir by shutters on its crest rather than by the action of sluices. The weirs of the future will probably be less in height above the canal bed and be all fitted with movable shutters on the crest. Broad and strong floors are essential in all under-sluices, and, as a rule, breadth of floor is more efficacious than deep curtain walls. It is better to prevent pooling below a floor

* 'Lectures on Irrigation Works in India,' by Col. F. H. Rundall, C.S.I., R.E., 1876, No. V.

by surface protection than to guard against the danger of it by deep-seated foundations. It is always desirable to have a long river wing between the weir and the under-sluice floor, this wing may advantageously be carried to a greater length below the line of the weir toe than the under-sluice floor itself. The crest of this wing should be above the level of the weir crest at the upper end, but it should slope downstream to 2 or 3 feet in height at its lower end. The velocity through the sluices is always greater than that over the weir, and there is a tendency for a strong circular eddy to be formed where the two currents join: a long river wing separates these currents and assimilates the velocities. The under-sluice floor should generally be at the level of the deep bed of the river, but, if it is possible to put it lower, without inordinate expense in laying the foundations and in other points of construction, an advantage is gained.

It has been thought that the ventage of under-sluices in any particular case should bear some proportion to the discharge of the canal which takes off above them, and, if any rule can be deduced from existing examples, it should apparently be that the ventage of the under-sluices below the level of the weir crest level should not be less than double the ventage of the head-sluice: but in this matter the practice varies greatly. In some Madras examples which have been successful, the ventage in the under-sluices is about the same as that in the head-sluices above them. Similarly, if the ventage of under-sluices be compared with the total obstruction offered by the weir, which is another standard which has been suggested, it will be found that the same great difference of practice exists and that no rule can be deduced. The amount of ventage required is less in the case of rivers with small slopes. The following table, which is only approximately correct, gives some statistics of the under-sluices of different weirs.

The earlier examples of under-sluices with small vents of only 5 or 6 feet in width were generally worked with wooden draw-gates and sometimes with baulks dropped into grooves. Plate XLVII. shows the under-sluices of the Kistna weir in Madras (constructed in 1854–55) and the method used for working the gates. The system of baulks has been abandoned in all recent examples as too clumsy, and, in most cases, far too slow for safety; as, in the event of a rapid rise in the river, it is not possible to get the baulks taken out in time. In some cases needles are suitable: especially in rivers where no rapid manipulation is necessary. Both needles and draw-shutters are used in the under-sluices of the Cavour Canal, on the Po in Italy: in that case the

VENTAGE OF UNDER-SLUICES.

	Approximate Total Length of Weir and Sluices between Abutments.	Average Height above Original Bed.	Lineal feet of Ventage in scouring Sluices.	Area of Waterway of Head Sluices below Level of Weir Crest.	Area of Waterway of scouring Sluices below Weir Crest.	Proportion which the Area of scouring Sluice bears to the Total Obstruction offered by the Weir.	Remarks.
	feet.	feet.		square feet.	square feet.		
Upper Coleroon Weir	2,800	5 7	111 48	?	555 336	1 to 12	Eight sets of sluices distributed; canal on one bank. Two sets of sluices; no canal.
Mahanuddee Weir ..	6,400	12½	640	720	8,000	1 „ 9	One set of under-sluices, and one set of centre sluices; canal on one bank.
Sone Weir	12,500	8	1,152	2,340	9,216	1 „ 10	Two under-sluices; one set of centre sluices; canals on both banks.
Ravi Weir (Madhupore)	2,800	3	240	1,035	1,320	1 „ 6	One set of sluices; one canal.
Sutlej Weir (Rupar) ..	2,700	9½	240	1,462	2,280	1 „ 10	„ „ „
Jumna Weir (including the island) at head of W. J. Canal ..	3,400	6	547	..	3,850	1 „ 5	One set of under-sluices on each bank, and a canal on each bank, but one is never used. The weir is diagonal to the stream; no accurate comparison can be made in this case.
Ganges Weir (Narora)	2,200	10	304	1,470	3,040	1 „ 12	One set of under-sluices; one canal.
Jumna Weir (Okla) ..	2,600	10	96	504	1,056	1 „ 23	„ „ „

draw-shutters have a bar of flat iron attached to them pierced with holes at close intervals: the shutters are raised by long levers with studs at the end which fit the holes in the flat iron: but the greater portion of the ventage of these under-sluices is manipulated by a movable needle dam which is similar to that employed in the under-sluices of the Eden Canal in Bengal, which are illustrated in Plate XLVIII. The needles bear against skeleton gates which are released simultaneously by the gearing in the pier. A long rope is strung through the eyes on the tops of the needles, and they are picked up with it after the sluice is open.

In the Mahanuddee weir (Plate XXXVII., page 136), the under-sluices consist of vents of 5 feet each only, with wooden draw-shutters: these are manipulated by a wooden derrick which is placed on the low piers of the sluices and moved from vent to vent as necessary. The arrangement is very primitive. But the centre sluices of this weir and the under-sluices of the head-works of the Midnapore Canal (Plate XXXVIII., page 138), consist of movable dams which are a modification of those introduced by MM. Thénard and Mesnager on the river Isle in France.

The movable dam* (Plates XXXVIII. and XLIX., page 170, Figs. 1 and 2), consists of two rows of wooden shutters placed back to back; both rows of shutters are very strongly hinged to a beam bolted down to the flooring of the sluice; the back, or downstream row of shutters is about 18 inches higher than the front row. The shutters of the Mahanuddee weir are about 7 feet wide; the upper ones are 7 feet 6 inches and the lower ones 9 feet high. There are seven shutters in each bay of the movable dam or centre sluices, and ten bays or vents, each 50 feet wide; each bay is separated from the next one by a stone pier 5 feet thick, on which the gearing for working the shutters is fixed. In the Cossye weir there are only three bays of 50 feet; each bay contains eight upper and eight lower shutters, the upper ones being 6 feet and the lower 7 feet 9 inches high. The front shutters fold down on the floor upstream; the back shutters downstream. A beam in front of the upper shutter is bolted down to the floor in such a position that the top of the shutter is just in a line with the upstream face of the beam; the top of this beam is about 3 inches below the top of the central beam, so that the shutter slopes slightly downwards from its heel when lying on the floor. The lower ends of the retaining chains are fastened to the beam in front, and the upper end to the castings on the back of the battens

* Taken from the author's paper in vol. lx. 'Proceedings of the Institution of Civil Engineers,' 1880.

of the front shutter. These chains are not fixed in a plane at right angles to the face of the vertical shutters, but diagonally, both sloping inward towards the centre of the shutter; the object of this is to prevent the upper half of the chains falling on the top of the lower half under the shutters, and preventing them from going down flat on the beam G. The chains now fall of their own accord, as the shutters descend, into a loop; a slight hollow is purposely left in the floor, in which this loop lies, so that, when the shutters are down, they are clear of the chains. The front shutters being down, hooks, attached to the bar in front of each shutter, are revolved by the bar until they catch the castings bolted to the face of the shutter.

When the Mahanuddee shutters were first put up, it was thought that they would lift of their own accord if these hooks were thrown out of gear when the stream was flowing through the sluices; but this only happened occasionally, when some bank or impediment directed the force of the stream under the shutters; and it was found that, even if the shutters were lifted an inch or so, the stream sometimes pressed them down again on the floor instead of lifting them. Another difficulty was also met with. After the shutters had been down perhaps for a few months, small water-worms used to construct cells between the shutters, the beam, and the floor—cells which stuck the shutters down so tightly that force was necessary to break the crust. For these reasons the following plan has been adopted:—A rod of iron, about 2 inches in diameter, is fitted along the face of the beam in front of the upper shutter; at one end of this rod a handle is arranged, so that the rod can be revolved about one-quarter of a revolution. The rod bears in the castings fixed to the face of the beam. On this, under the centre of each shutter, a cam is keyed, which, as the bar revolves slightly, lifts the shutter as soon as the hook is out of gear. The seven cams fixed to each rod to lift the seven shutters in each bay are set at slightly different angles, so that, as the rod revolves, they come into operation on the shutters one after another, and the shutters rise in the same order as soon as the stream catches them.

The back shutters, which are erected by hand after the front shutters have been raised and the current has been stopped, are always used to retain the pressure of the water when the movable dam is closed. When they are erected they stand inclined at an angle of about 15° downstream. They are supported at the back by struts, one of which is hinged to the batten at the back of each shutter at about three-eighths of the height of the shutters from the top. To the first shutter

in each bay two struts are fitted. Between all the shutters a T-iron is hinged to the castings fixed on the centre beam, which has a strut hinged to it similar to those on the shutters. These last struts and T-irons are altogether independent of the shutters; they are loose from them, and are put up separately after the shutters are raised. The heels of all the struts rest, when the shutters are up, in the lugs of the iron shoes, which are bolted down to the floor. The shutters are raised one by one by men standing on the floor below. They first lift the shutters—there being, of course, little or no water on the floor—and support them by the first-mentioned struts. After any two contiguous shutters are up, the strut between them is raised, the foot of the T-iron is inserted between the shutters, and they both bear against the head; a joint fairly water-tight is thus formed. To let the back shutters fall when a flood is expected, a bar, arranged to slide in guides on the floor close to the heels of the struts, acts in the same manner as the bar used in M. Chanoine's falling dams in France. Studs are welded on to it at intervals, which catch the heels of the struts as the bar is drawn along the floor by the gearing fixed in the pier. These studs are so fixed that the shutters fall one after another, the studs coming into gear with each pair of struts consecutively, the shutter which has the two struts L attached to it being the last to be let down. As the first shutter falls, the second is supported by its own strut, and the neighbouring T-iron strut, at the joint between itself and its neighbour. When the sixth shutter is let down, the seventh, were there not two struts attached to it, would be twisted by the force of the stream; it is to prevent this that double struts are attached to the last shutter.

As there is generally little or no water on the apron when the sluices are opened, men can nearly always walk about behind the shutters as they are being let down; indeed the back shutters are not unfrequently let down by men with crowbars pushing the struts out of the lugs on the shoes; or sometimes the men knock the struts out of the lugs by a wooden beam which they jump against them.

This form of movable dam has one great disadvantage, this is the severe shock which the retaining chains have to bear. The chains were constantly breaking, both in the Mahanuddee and Cossye weirs. On the Mahanuddee there are now 1¼-inch stud chains; they were at first ⅞ inch. On the Cossye weir the constant breaking of the chains gave so much trouble that the engineer in charge has substituted folding links (Fig. 2). On one occasion the front beam was pulled up from the floor. The strain on each chain of the shutters of the Cossye weir, 6 feet high by

6½ feet broad, is about 16 tons. This kind of shutter has never been raised against a greater head of water than about 6 feet 9 inches. The front shutter is only used when the level of the river has fallen to at least 6 feet above the floor of the weir, and frequently the engineers hesitate to use the shutters until it has fallen lower. The mode of working this form of dam is simple. Supposing the shutters to be flat on the floor, and the stream running through the sluices, if it is desired to lift the front shutters, the bar in front of the upper beam is made to revolve by the handle on the pier, the hooks are released, and the cams on the bar raise the shutters, one by one, a few inches above the beam; the stream then rushes beneath and throws the shutter violently up into place. When all the front shutters are up the men go below on the floor of the sluice and lift the back shutters by hand, having first drawn back the disengaging bar. The struts are placed in the lugs, and the back shutters are then ready to receive the pressure of the water.

It has been found that in a dam constructed on this principle, 500 lineal feet of shutters can easily be lowered in one hour with a head of 6 feet of water, and that with a similar head an equal length can be closed in twenty-five minutes; that three men standing on the floor are sufficient to knock away the back struts, with safety to themselves; that the back shutters are not damaged as they fall on the floor, because sufficient water escapes as each shutter falls to form a cushion for the other shutters to fall into. Twelve men are necessary to lift each of the back shutters into position.

In the Sone weir (Plate XLIX., Figs. 4, 5, 6, and 6*a*) each of the three sets of river sluices is fitted with a movable dam, designed by Mr. Fouracres; the under-sluices on each flank are divided into twenty openings of 20 feet 7 inches wide; the piers between the openings are 6 feet thick and 32 feet in length, and the tops of the piers are 10 feet above the bed of the river, that is 2 feet above the crest of the weir wall, which is 8 feet above the sluice floor. About the centre of each opening the level of the floor is raised 9 inches, and thicker floor stones are laid; the object being partly to have heavier stones for the lower edge of the shutter to oscillate against, and partly to form a recess, so that the shutter may lie snugly on the floor. Each opening is fitted with two shutters; the upstream one is 21 feet 3 inches in length, and 9 feet 9 inches high. This shutter is pivoted at its lower edge, and turns on two strong cast-iron gudgeons working in sockets built into the piers. The shutter being 8 inches broader than the width between the piers, has, when vertical, a bearing of 4 inches on either side against each

pier; but this has been found unnecessary, as the telescopic struts are sufficiently rigid to withstand the pressure; and when the packing in the hydraulic brakes becomes worn, the shock against the pier injures the masonry. The piers are recessed 5 inches deep for the extent required to enable the shutter to oscillate freely between the horizontal and vertical positions. At the back of the shutter six struts are fitted, which are the chief novelty in this system; they answer the double purpose of supporting the shutter when vertical, and of breaking the force of concussion against the piers when the shutter is suddenly raised with a 9-feet depth of water running through the sluices. There are six backstays to each shutter; each consists of two cast-iron brackets, the first firmly attached to the stone floor, the other to the shutter; to the lower bracket is hinged an iron bar, $2\frac{3}{4}$ inches in diameter, and to the upper bracket a wrought-iron pipe, $3\frac{1}{2}$ inches internal diameter; the bar is inserted into the pipe, and the two thus form a telescopic strut. On the lower extremity of the bar is a collar which, when the shutter is vertical, is in contact with a ring shrunk on the end of the pipe; the pipe thus forms a rigid strut supporting the shutter at the back. On the rod, which is $\frac{3}{4}$ inch less in diameter than the pipe, are shrunk two guide rings, and above the upper ring is fixed leather packing similar to that of a hydraulic ram; this packing makes the head of the rod into a piston, which, when exposed to the force of the water, fits tightly into the tube. In the pipe are three small holes $\frac{3}{16}$ inch in diameter; the lower one is about 4 inches above the leather packing of the rod when the shutter is horizontal and the telescopic joint drawn out; another hole is at the top of the pipe, a little above the leather packing when the shutter is vertical and the telescopic joint shut up; between these holes is the third one. The action of these backstays is as follows:— When the shutter is down and the telescopic joint drawn out, the water running through the sluices enters and fills the pipe through the $\frac{3}{16}$-inch holes, and flows probably past the piston, for the leather packing becomes loose as the rod is drawn out; the pipe is then full of water. As soon as the shutter begins to rise, and the telescopic joints consequently begin to shut, the leather packings, being opposed by the water in the pipes, become tight, and the water can only find means of escape through the small $\frac{3}{16}$-inch holes; its efflux is therefore much retarded, and a brake is placed on the motion of the shutter: the resistance increases as the piston passes the first hole, and attains a maximum after the piston has slid past the second hole, and the shutter comes up gradually to the vertical position, the water being

expelled in a jet from the topmost hole. When the shutter is lying down on the floor, and the telescopic backstays are extended at full length, the holes in the pipes rest on indiarubber buffers secured to the back of the shutters. This completely closes the holes and prevents sand or silt accumulating within the pipes. At first the holes were placed on the top of the pipes, and they became clogged by sand.

A vertical bar, with a catch at the lower end, worked by a handle on the pier, is fixed to retain the shutter horizontally until it is required to be lifted.

The downstream shutter is 20 feet 7 inches long and 9 feet 7 inches high, fitting between the two piers without any recess; on the upstream side of this shutter seven tension bars are hinged, first to brackets bolted to the floor above the shutter and then to the shutter itself. The shutter oscillates about the centre of the bracket pin, and the tension rod about the centre of the pin of the bracket which is fixed to the floor; so that, when the shutter falls downstream, the lower part slides along the floor towards the fixed bracket, and finally sinks into the horizontal position shown by dotted lines (Plate XLIX.). At the back of every alternate shutter a trough is formed by a curb of ashlar 12 inches high, which stretches across from nose to nose of the piers; this trough remains always full of water, and forms a cushion to break the fall of the shutter should it be necessary to let it down when there is no water on the apron. After every alternate shutter has fallen there is sufficient water on the apron to break the fall of the intermediate one.

The tension-rod is hinged to the shutter a few inches below the centre of pressure when the water is level with the top of it, so that when the river rises slightly, the centre of pressure is soon raised sufficiently above the centre of oscillation of the tension-rod to overcome the friction of the lower edge of the shutter on the floor; the shutter then falls into the horizontal position, and the flood is free to pass. A chain at each end retains the shutter, if necessary, against any head of water. Pieces of kentledge are fastened to the front of the shutter to keep it steady and to prevent it from being raised and knocked about by the stream flowing over it. The shutter when lying on the floor is inclined slightly upwards, the top being a few inches higher than the heel; the stream impinges on the inclined surface of the shutter, and thus presses it down tightly on the floor with a pressure varying with the velocity of the stream. The shutter remains steady so long as the water is flowing with a velocity of more than 2 feet a second.

The usual velocity is about 17 feet a second. The kentledge is only wanted in case the water below the weir rises nearly level with that above it, when the velocity would be so small that the shutter might float and be damaged by the stream. In each of the upper shutters is a small sluice, which can be opened by hand, to fill the space between the two shutters with water, and thus place the pressure on the lower shutter. In front of the upstream shutter a groove is cut from top to bottom of the piers, into which logs of timber can be dropped when repairs are necessary, or in case any accident should prevent the shutters from being lifted.

During the dry season the water is retained in the weir-pool by the back shutter, which is secured in position by two chains; one end of each of these chains is fixed to a stud in the centre of the pier, the other end is slipped into a let-go gear on the top edge of the shutter. When floods are expected, and it becomes necessary to make arrangements for opening the sluices, the back shutter gear is let go, so that, should the flood rise suddenly, the shutters will upset of their own accord and let the water pass freely.

At any time when it is desired to close the under-sluices, a light portable foot-bridge is run across on the top of the piers, which are then probably only a few inches higher than the water above the weir, so that men can easily pass along the whole length of the dam. In the next place a hook, having at its upper end a cranked shoulder fitting into a lever attached to the pier, is placed under the angle-iron which is fixed on the top edge of the front shutter; the lever is then drawn tight by a light threefold tackle attached to the pier; when this has been done on each of the piers and all is ready, the catches which keep the shutter down are withdrawn, the men draw down the lever with the tackle until the upper edge of the gate has been lifted about 8 inches, and the stream then raises the shutter slowly into the vertical position, the hydraulic brakes preventing any shock.

It has been found in practice on the Sone weir, that these shutters can be safely lifted, without shock, against a head of 10 feet of water, that is, when the water in the pond above the weir is level with the top of the piers; they have been frequently worked under these conditions; the greatest head against which other shutters on any other weir have been lifted is believed to be about 6 feet 9 inches only. It is a sight worth seeing to watch a stream of water, 20 feet broad and 8 or 9 feet deep, flowing with a velocity of 17 to 20 feet a second, suddenly checked by a single gate 20 feet long by 10 feet deep. The water, when the

shutter reaches the vertical, rises in a wave 1 foot or 2 feet above the top of the shutters and piers, and flows over for a few seconds before it sinks to the mean level of the stream.

When the front shutters have been raised, it is advisable to put up the back shutters at once, and to refold the front shutters on the floor; because, should a flood come down unexpectedly, the back shutters will be ready for any contingencies, and also because there is always danger of silt, sand, stones, and rubbish collecting before the front shutters.

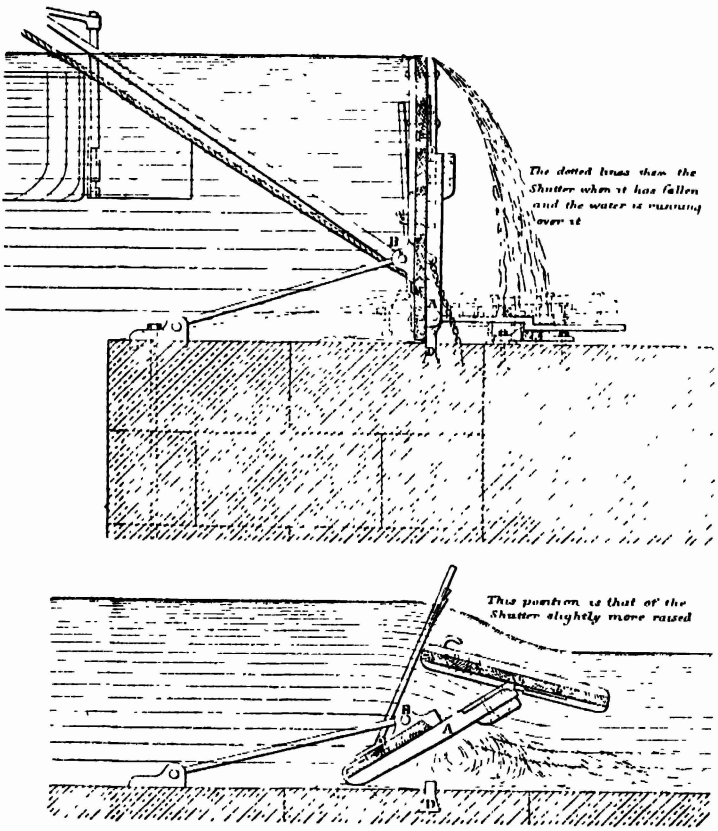
To raise a back shutter the tackle used for hauling down the levers of the front shutter is again employed; one block being hooked to an eyebolt on the upper edge of the back shutter, and the other block to a rag-bolt in the side of the pier, four or five men haul on the tackle and pull the shutter into a vertical position. When both shutters are up, the men proceed to lower the front one. The valve in the front shutter is opened, and the space between the two filled with water; the back one now retains the whole pressure, and the front shutter simply rests in the water, the pressure on each side of it being equal. The front shutter is then pushed up stream by two men on each pier pressing it down with a pole or boathook until it rests on the floor, so that the catches can be brought into gear, and it is safely fixed ready to be again lifted. Should it be found necessary to upset the back shutter when the water above the weir is below the top of it, and when the centre of pressure is consequently below the axis, a boom or spar, with an eye-bolt at one end, is applied against the top of the shutter on the batten next the pier, and the tackle before used is hooked into the eye-bolt at the other end of the spar which is then boomed out against the shutter until it falls. It takes about half an hour to fully manipulate each vent of the under-sluices. Fig. 7 shows some modifications in the details which were suggested by Mr. Fouracres for any other sluices constructed on this principle.

A movable dam was constructed on one of the weirs of the Arrah Canal (Plate L) in Bengal, on the system which M. Chanoine adopted in France.

Another form of under-sluice shutter or movable dam was constructed and subjected to experiment by Mr. Fouracres. It has not fulfilled successfully the essential condition for all dams on Indian weirs, namely, that they should be capable of being lifted without shock against a head of 8 feet or 10 feet of water, but it is nevertheless worthy of attention, for it possesses several advantages as regards lifting against

a head of water over the system of M. Chanoine,* to which it is in some respects similar.

Each shutter consists of two parts. The lower part is made of two wooden battens, A, 4 feet long, attached at their lower ends by a longitudinal plank about 2 feet broad. The upper shutter is hinged to the top of the battens of the lower one in the centre of its height; it consists of planks and battens with a counterbalance weight and hook at its lower edge. The lower shutter is hinged by a casting B to a tie-rod



FOURACRES' DOUBLE TUMBLER SHUTTER.

5 feet long, the upstream end of which is hinged to another casting, firmly bolted to the cut-stone floor of the weir. This casting B is attached to the lower shutter at such a point that, when the shutter is in the position shown in the upper figure, the centre of pressure of the

* M. Chanoine's system is described in Paper No. 1655 'Proceedings of the Institution of Civil Engineers,' and in No. 1*a*, vol. vii. 'Roorkee Professional Papers.'

water on the whole shutter is about 3 inches or 4 inches above the centre of the castings B. Short chains are attached to the heel of the lower shutter, to prevent it riding over the stops D, which bear against the heel of the gate when it is in the vertical position. To the heel of each lower shutter two wrought-iron bars. E are hinged, which, when it is erect, catch into castings on the floor, and will hold the shutter against any head. There is a draw-bar on the floor by which these bars can be released.

When the catch-bar E is released the shutter will fall if the water is level with the top or above the top of it ; but until it is released the shutter will stand, for the centre of pressure of the upper shutter is always below its point of oscillation If it be desired that the dam should be self-acting as regards opening, the catch-bars may be thrown out of gear before the floods arrive, and the shutters will then fall of their own accord one after another in the order of their sensibility. To raise the shutters from the floor against a head of water is rather troublesome ; the hook on the upper shutter has first to be caught by a boat-hook from a barge moored in the river above the weir. When this is done the shutter is gradually pulled up by a winch on the barge. As it is being raised the upper shutter is kept inclined slightly against the stream, so that it presents little more than the area of its cross section to the resistance of the water. The lower shutter, as it gradually rises into the vertical position, presents above its axis of rotation B only the area of the battens A to the resistance of the stream ; but below that axis the boarding, which is attached to the heels of the battens, opposes a considerable area to the stream, so that, after the shutter has been slightly raised from the floor, the pressure on the planks below the axis B assists the lower shutter into the vertical position ; when the lower shutter has reached this position it rests against the stops D, and the catch-bar E falls into gear with the castings ; the lower shutter is thus fixed securely. As soon as it is ascertained that this is the case, the upper shutter is temporarily fastened in a horizontal position by a batten which is hinged to the front of the lower one. This is done that the water may flow over the top of the planks on the heel of the lower shutter, and that the level of the water above the dam may be raised as little as possible. After all the shutters have been raised, the battens holding the upper ones are pulled away by a boathook, and they rise into the vertical position, partly by the action of the counter-weight and partly by the force of the stream. This form of movable dam has not been actually adopted on any weir.

In the North-West Provinces and the Punjab nearly all the under-sluices on the river weirs are fitted with draw-gates which are raised by a traveller running on rails laid above high water level on the tops of the piers (see Plates XXXIII, p 128, and LII) The vents are generally 20 feet in the clear; the gates run in cast-iron grooves in the piers, which, in most cases, are carefully planed and very accurately fitted. There are usually two gates in each vent, one above the other, but running in separate grooves, they are made of wrought iron, and vary in height according to the necessities of the case Thus in the Myapore under-sluices of the Ganges Canal there are two gates, each 6 feet in height; on the Ravi weir of the Bari Doab Canal, the lower gate is 3 feet and the upper one 4 feet in height, on the Sirhind Canal weir at Rupar, both gates were originally 5 feet in height, but the upper one has now been increased to $7\frac{1}{2}$ feet, because the water level has been raised by the falling shutters which have been placed on the crest of the weir. The shutters on the Jumna Canal under-sluices are each 4 feet 3 inches in height In all these cases the design is very similar to the under-sluice gates of the Chenab Canal, which are illustrated in Plate LI., but in that case, there are three gates instead of two The gates overlap each other when they are down in place, about 6 inches, so that they can, when necessary, be made quite watertight by caulking the interval between them with a pole bound round with straw, which is dropped on to the top of the lower gate These gates are lifted by chains hooked to the shackle at either end of the gate by the traveller (Plate LII.), which can be run over each gate in turn on the rails which are laid over the sluices In the case of the Chenab Canal the lifting chains are attached to the drums on each end of the traveller, but in some cases—in the Western Jumna and Sirhind Canals for instance—there are chains permanently attached to the gates, which are hooked on the piers, and are brought into gear on the traveller when a gate has to be lifted. The traveller is fitted with a powerful brake, which is used when the gates are lowered, just to keep a slight check on the chains as the gate runs down in the groove, or, it may be, to lower the gate gradually if it is not necessary to drop it quickly in order to force it down into place against a strong stream. The gates, it will be noticed, are fitted with rollers, so that the friction is greatly reduced when they are dropped against a head of water. In some cases these gates, when they have been fitted without rollers, have been found to stick when they were lowered against a heavy stream, and, on the Ganges Canal, an arrangement somewhat similar to that used on the head-sluices of the Sone

Canals (Plate LVIII., page 184) was introduced by which the gates could be pushed down by a pole actuated by the traveller. In that case, however, it was not found necessary to use this arrangement, as the gates were fitted with rollers and worked quite easily.

This system of draw-gates for under-sluices has the objection that it is slow, and consequently dangerous in those cases where floods rise rapidly. In the case of double gates, such as those on the Sirhind Canal, it takes about five minutes to lift and fix the upper gate in place, and ten minutes to do the same for the lower gate, even when the traveller has not to be shifted. The systems of under-sluice gates which are employed on the Orissa and Sone Canals in Bengal, which have been described in this chapter, are much quicker in their action.

The system of draw-gates illustrated in Plates LI. and LII. has been adopted, with some modifications, on the Barrage across the Nile in Lower Egypt (page 160), and in the lower vents of the great Escape (page 189) at Qusheshа in Middle Egypt.

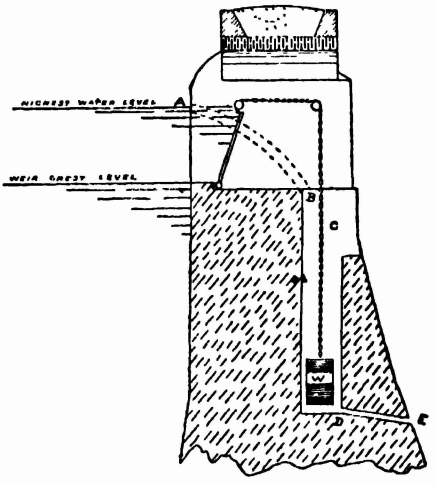
In the large masonry dam of the Bhatghar Reservoir in the Bombay Presidency there are fifteen vents, or under-sluices (as they are called), which have been constructed with the object of preventing the deposit of silt in the reservoir (see page 79). Each of these vents * is 8 feet high and 4 feet wide in the clear, as shown in Plate XX., page 78, and they are subjected to a head of over 80 feet when the reservoir is filled to the highest flood-level. Plate LIII. shows the details of these gates. Each cast-iron gate with its steel lifting-rod 4½ inches in diameter weighs about 4½ tons. The top length of the lifting-rod is square in section for a length of 12 feet 6 inches, machined on all sides to work in a square guide, also planed true. The top 11 feet 4 inches of the rod is screwed, and on it fits a gun-metal nut and collar, which fits in a cast-iron thrust-box, bolted to the masonry at the top of the dam. A cast-iron capstan-head fits the nut, and is worked by six wrought-iron arms, the end portions of which are bent so as to be horizontal at a suitable height. Additional leverage can be obtained, if necessary, by means of wrought-iron piping slipped over the ends of the bars. The screen in front of each gate consists of wrought-iron double-headed rails, 2½ feet from the face of the sluice, weighing 66 lbs. to the yard, fixed in horizontal rows 1 foot apart, the ends resting in grooves in the masonry piers, and kept in position by vertical bars 1¼ inch in diameter. The calculated

* This description is taken from page 18 of the 'Report on the Nira Canal Project,' published by the Government of Bombay in 1892.

maximum velocity through the sluices is 60 feet a second, and it is estimated that the greatest possible pressure on each rail will be less than one-third of the safe load and one-fifteenth of the breaking load. The only defect to be noted in the design is the position of the cage of rails with respect to the sluice. It should have been at least 12 feet in front instead of only $2\frac{1}{2}$ feet. This could have been done at some extra expense by prolonging the piers upstream, and the cage at this distance would have minimised the danger of brushwood interfering with the working of the gate The two sluices for drawing off water for irrigation, at reduced level 266·20 and reduced level 292·20, are each 3 feet square, and similar in design to the under-sluices. A mistake was, however, made in these two gates by providing brass facing on the gates only, the frames on which they work being only planed cast iron. The result was that in two seasons the faces of the frames were pitted by rust, and there is no doubt that eventually brass-faced frames will have to be substituted.

The waste weirs of large reservoirs are necessarily constructed with a crest level which is below the maximum or flood water level in the reservoir, while the main dam, which forms the reservoir, is constructed to retain the water up to that maximum flood-level. If the waste weir is an open one, that is if there are no shutters, or planks, or needles on its crest, the maximum level of the water impounded in the reservoir is necessarily the level of the waste weir crest, and not the higher level which the main dam is capable of sustaining, so that the full quantity of water which the works are capable of impounding is not stored, for the level of the surface, after a flood has passed, falls to the crest of the waste weir. In many cases waste weirs are fitted with planks or needles, so that the ventage of the weir can be closed after the flood season, but when there is still some discharge from the catchment, and the water surface is thus raised up to the full level which the main dam can sustain; but this plan is a dangerous one, especially in those cases where sudden floods occasionally occur after the monsoon season has passed, for in that case it may not be possible to remove the planks or needles in time, and the result may be disastrous. In many cases it has been the custom to cut the waste weir to different levels in parts, and to close these parts one by one with low earthen embankments, which, in the event of a sudden flood would cut away rapidly by the action of the water as soon as they were topped by the stream. But this method is, at the best, an unsatisfactory one, partly because it is uncertain in its action, but mainly because it is a lengthy business to remake the embankment

after a sudden flood has destroyed it, and it may be impossible to do it in time to refill the reservoir to the full level. Experience in the larger reservoirs in Bombay* has shown that, to ensure the full additional storage above the level of the waste weir crest, a method which is entirely automatic both as to opening and closing is essential. One solution of the problem of an automatic gate for waste weirs was found by Mr. Whiting, who designed a self-opening gate, which will be understood from the sketch in the margin :—



WHITING'S SELF-ACTING WASTE WEIR GATE.

The gate was hinged at its lower edge to the crest of the waste weir, and was capable of falling downstream flat on the crest. It was retained in place by the chain and counterweight W so long as the water was below the maximum flood-level. The counterweight hung in a chamber C D, which had a small outlet pipe D E at the bottom, and a large inlet pipe A B (led through the pier) at the top. When the water had risen to such a height in the reservoir that the inflow into the chamber through A B was greater than the outflow from D E, the chamber filled and the counterbalance W lost weight sufficiently to allow it to rise ; when the level in the reservoir was so reduced that the water flowing into the chamber through A B was less than that discharged through the pipe D E, the chamber emptied itself and the gate would rise as soon as the weight of the water flowing over it would permit the counterbalance to raise it. The principal objection to this gate was that it would not lift until the water had fallen to about 2 feet above the waste weir crest level, and the storage of a considerable depth of water was therefore lost. A gate which was more tender in its action was found to be necessary, and the design which is shown in Plate LIV. was worked out by Mr. Reinold.

This design is that of the automatic gates which are actually being erected on the waste weir of the Bhatghar dam near Poona, in Bombay

* Memorandum on Waste Weir Shutters in the 'Report of the Nira Canal Project,' Bombay, 1892.

(page 76). This form of gate is very suitable where there is a clear overfall from the sill of the sluice, but it cannot be adopted in ordinary river weirs. The gate, which is of iron, is suspended by chains running over pulleys above it; there are two chains to each gate, both of which are attached to a single counterbalance weight working in a chamber at the back of the sluice. This chamber has an outlet pipe at the bottom which discharges at the back of the weir, and an inlet pipe at the top which is supplied from the full supply level of the reservoir. The discharge of the outlet pipe is less than that of the inlet pipe when the water in the reservoir is at or above full supply, so that, under those circumstances, the counterweight chamber is maintained full of water. When the water in the reservoir is below full supply level the chamber becomes empty and the counterbalance weight retains the gate at its highest point; but when the water rises to full level and flows into the chamber, the counterbalance loses weight * to such an extent that the excess weight of the gate over the diminished weight of the counterbalance is sufficient to overcome the small amount of friction, and the gate moves vertically downwards, and continues to do so as long as the water in the chamber rises. But when the discharge through the opened gate has so far reduced the level of the water in the reservoir, that the supply entering the chamber is insufficient to keep up the level of the water in it, the counterbalance regains the weight necessary to lift the gate, and it rises up to the top of its run. It will be noticed that the gate runs on large rollers working in cast-iron grooves. The bearing surface of the gate and the seating on the cast-iron frame on the piers are tapered so that there is no sliding friction when the gate falls; it recedes from the seating immediately it falls below its highest point. Set screws are provided, so that the position of the gate with reference to the seating can be accurately adjusted. Each of the gates weighs 6328 lbs.; the counterbalance is $7\frac{1}{2}$ feet by $2\frac{3}{4}$ feet by $5\frac{1}{2}$ feet, giving a displacement of 7051 lbs.; it is made of wrought iron $\frac{1}{4}$ inch thick; a certain amount of sand is added, making the total weight 9200 lbs. When the weight is free in air, the power available to draw up the gate is (9200 – 6328 lbs.) 2872 lbs., and when it is immersed in water its effective weight is reduced to (9200 – 7051) 2149 lbs., which is 4179 lbs. less than the weight of the gate. The weights can be adjusted to provide exactly equal power both for opening and closing the gate, by making the counterbalance equal in weight to the entire

* This description is taken from a Note by Mr. W. H. Le Quesne, Executive Engineer, Nira Canal.

canal at the different seasons. When the water level on the upper side is above the soffit of the vent, the formula employed is that for the discharge through a submerged aperture,* but when the water level is below the soffit, the formula for a submerged weir is the one to be employed. It is generally a good plan to allow ample ventage in head-sluices at the off-take: a few extra vents add very little to the cost, and may often be very valuable at times when the supply in the river is low. The floor of a river head-sluice should generally be at least as solid as that of the under-sluices, for, although it has not to withstand the great velocity and heavy rolling friction of the flood, it is more liable to be "blown up" by pressure from below. An under-sluice is subjected to the greatest strain, in this respect, when the water in the pool above the weir is level with the weir crest, but the head-sluice has to bear the difference in level between the high flood of the river and the ordinary canal surface, which is often greater than that brought upon the under-sluice. Several head-sluices in Bengal have been wrecked by the floors being "blown up." One case was that of the head-sluice at Panchkoorah, Plate LVII., on the Midnapore Canal. General Rundall writes of this sluice as follows† :—"The work in question is situated at the head of a bend of a canal supplied from a branch of the river Cossye, and, having to supply an area of only 20,000 acres, it is a small work, that is, it has only two vents; but the rise and fall of the river being great, the sluice itself was obliged to be built high. The difference of level between the surface of the river in full flood and the water in the canal is 18 feet. After having been in use for three or four years, during which interval one high flood had occurred, yet on the occurrence of another similar flood it suddenly without any warning blew up, the only assignable reason for the catastrophe being that the water from the river must have been forced under the upper curtain wall, and that the flooring was not able to bear the great pressure that was thus brought upon it. On rebuilding the work, the dimensions were therefore increased, principally those of the flooring; the curtain walls which before were 6 feet deep below the floor were increased to 10 feet, and further protected by a row of piles sunk 15 feet below the foundations. The width of the floor was made 80 feet, and its thickness increased from 4 to 6 feet. An apron of brick blocks projects 50 feet beyond the floor on the canal side, and 30 feet on the river face. The velocity due to a head of 18 feet is about 30 feet

* See Appendix V.

† 'Irrigation Works in India,' Chatham Lectures, 1876.

per second, hence, though this work is but small compared with those constructed on the larger canals, yet it exhibits a good example of what works of this description are exposed to, and the precautions that are required under similar conditions. Being situated in the region of alluvial soil nearly 30 miles distant from any stone quarries, with only cart carriage available, it was not possible, on grounds of economy, to use stone for the mass of the work."

The vents of head-sluices are generally 5 or 6 feet wide only, and, as a rule, are controlled by draw shutters such as those shown in Plates XXVIII., XXXIII., and LVII. The shutters often work in plain stone grooves or even in brick ones, but in some cases, as in Plate LVIII., cast or wrought-iron grooves are fixed. Friction rollers are rarely fitted to these gates as they are at Rupar (Sirhind Canal). In those cases where screws are used for lifting and lowering the gates there is no difficulty in depressing them against a head, but where a travelling winch is used to lift the gates (as in the Sirhind, Sone, and Bari Doab canals) there is often some difficulty in getting them down. On the Sone canals, a spar is used to do this. The travelling winch which is used to lift the gates is anchored to the masonry, and the spar, which rests on the top of the gate, is pressed upon it by a chain attached to its upper end, which is wound up by the winch. In several cases, as has already been mentioned, the gates of river head-sluices are divided into two or even three parts. In most cases these run in the same groove and are fished from above, when it is necessary to lift them, and hauled up by a winch; but on the head-sluice of the Kistna Canal, at Bezwada, in Madras, a more perfect but more expensive method of three separate shutters in separate grooves, each with a screw of its own, is employed, Plate LVIII. In the head-sluice of the Cavour Canal in Italy, double shutters of the same size, one behind the other, in different grooves, are used. If one shutter, when dropped, does not close the vent, it reduces the discharge greatly: the one behind it is then dropped; it descends a little below the first one: the upper one is then raised and again allowed to run down: if this does not close the vent, the back one is again raised and dropped. These shutters are worked by a lever and not by screws.

Regulators within a system of canals are generally situated either at the point of bifurcation of a main canal, or across the channel immediately below an escape: in the former case the regulator is required in order to divide the discharge between the branches in the required proportions, and in the latter case to regulate the discharge of the canal by compel-

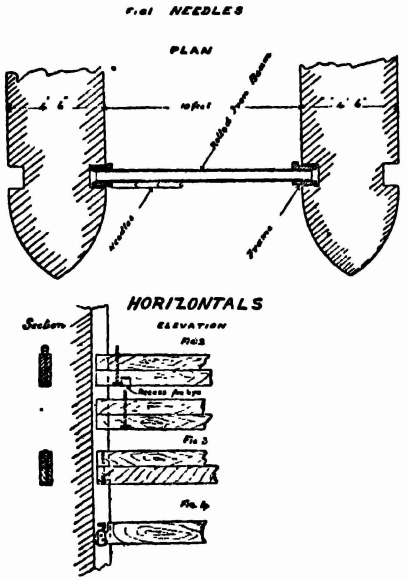
ling the surplus water to flow off through the escape instead of down the canal.

Plate LIX. is an ordinary design for such a regulator, in which the discharge may be controlled either by "khurrics" (baulks dropped into the grooves) or by gates manipulated by a traveller running on rails on the noses of the piers. At the Chamkaur regulator on the Sirhind Canal (which is placed immediately below the escape referred to in page 43), and in the Doraha regulator on the same canal, Plate LX., draw-gates worked by travelling winches, are used. But the system of regulation by baulks is more common and is less expensive. There is rarely a head of more than 6 inches or 1 foot on these works and baulks can be easily manipulated.

In the Sind inundation canals the regulators are usually worked by a system of vertical needles, as shown in Plate LXI. The needles are driven down by a maul, and raised by a lever on the parapet wall. The horizontal baulks which bear the pressure of the vertical needles are fixtures, usually, in the masonry. This system is employed in many regulators, such as that on the Eden Canal in Bengal, Plate LXII. In Bombay, Mr. Whiting introduced the use of needles made of sheet steel, which have been successful.

In Egypt the system of regulation, both on the inundation canals and on the regulating bridges placed on the dividing embankments of the "basins" (page 24), is, in most cases, similar to that just described, but the horizontal beams which bear the pressure are often made of rolled iron and not of timber. The regulators themselves are simple bridges, all of the same design, with vents generally 10 feet wide, piers about 5 feet thick, and the crown of the arch at the high water line. The depth to be controlled on Egyptian canals is very great: it is often 20 feet, and sometimes as much as 28 and 30 feet. The horizontal beams are not always fixtures in the masonry, but are lowered into place in a framework when they are required. A pair of shear legs is erected on the roadway of the regulator, and this frame is built up as it descends; it consists of four planks about 15 inches by 6 inches in section, two of which are inserted in each vertical groove of the regulator; between these planks the horizontal iron beams are bolted; they are put in place as the frame is lowered by the tackle on the shear legs, and are about 3 feet apart at the bottom of the frame, and the spacing is increased at the top according to the pressure. The needles generally used in Egypt are shaped as shown in the sketch Fig. 1, and are about 10 inches by 6 inches or so: they are made of pine. But the system of regulating by vertical

needles is tending to give way in Egypt in favour of regulation by horizontal baulks or planks. The group of regulating heads at Dêrut* on the Ibrahimiyah Canal (where a discharge of more than 30,000 cubic feet a second is dealt with, and where the depth of water over the floor of the regulators is over 26 feet at times) are entirely controlled by horizontal planks. The planks are about 10 inches broad and 4 inches thick, and they are raised by means of a fixed windlass over each vent. The difficulty is to get the planks down when a stream is flowing. The system adopted is to drop the planks one above another into the grooves and to jump them down with an iron monkey. The men get very expert at dropping the planks horizontally so that they do not jam in the grooves. The planks used to have eye-bolts in them, as in Fig. 2, by which they were fished with a hooked rod, but it was found difficult to catch the eyes in a strong stream. The system in Fig. 3, was then adopted, where the eye was under the protection of the groove. But the most approved plan is shown in Fig. 4 ; in this case the hook can be fished by a rod with an eye, instead of a hooked end, which is an advantage, as the eye is stronger, and the strap round the plank is found to be better than the bolt through it, as it does not weaken it.



NEEDLES AND HORIZONTALS ON EGYPTIAN REGULATORS.

There are several causes which render it necessary to have means of discharging water from a canal into a river or into a channel leading to a river. In the first place it not infrequently occurs that a heavy fall of rain puts an immediate check to, or perhaps will completely stop, all irrigation within a few hours. The cultivators close the outlets leading to their little channels, and the heads of the distributaries have to be closed or the banks will burst. The closing of the distributaries makes it necessary to reduce the discharge of the canal, or the same result would follow ; but this cannot always be done in time to prevent a larger dis-

* See Plate XII., Part i. page 32.

charge passing down than the channels are able to pass forward, or, if it is possible to carry on the discharge, it must be escaped from the canal system somewhere, if the cultivators will not utilise it on the fields. Escapes are in some cases necessary to carry off, from the canal, drainage water which may have been admitted into it through inlets; and they are of service when any accident to a masonry work or breach of the canal renders it necessary to reduce the discharge immediately. Reference has already been made (page 44) to the use of escapes for scouring out silt deposits at the head of canals when there is a sufficient volume of clear water available, after the flood season, to permit of water being run to waste. In Southern India escapes are usually termed "surplus sluices," and they are not infrequently used for the purpose just indicated. As a rule it is desirable to have sufficient power of escape on any canal to dispose of about two-thirds of the full discharge at the head: in distributaries of short length no escapes are necessary, but when they exceed about 10 miles in length, escapes, capable of carrying about one-third of the head discharge, add greatly to the ease with which they can be managed: and in some cases, especially where large tracts of rice are under irrigation, escapes are necessary to prevent the surplus water, which would otherwise flow out of the tail of the distributary, being used in an unauthorised manner for irrigation.

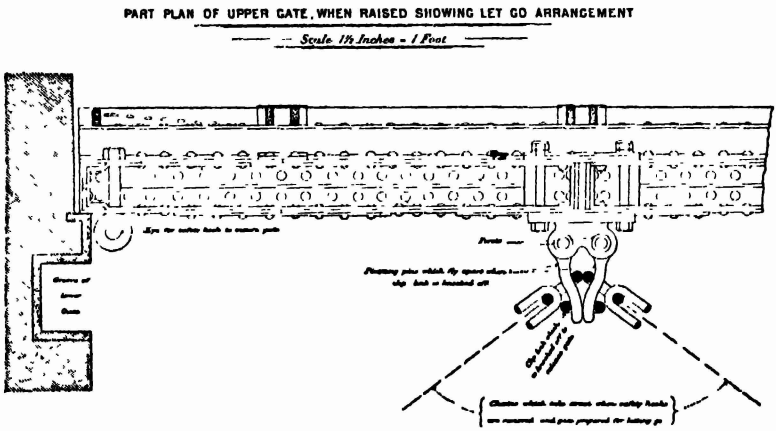
Escapes sometimes take the form of head-sluices with draw-gates, as in Plate XLIII., page 144, or as in the Indri escape in Plate LIX., where the gates completely close the opening when they are down. In some cases, as in the sketch on next page, which is typical of the escapes—or surplus sluices as they are called—in Madras, the gates are worked in the same way as in the previous example, by screws, but they do not close the vents: the crests of the gates, when down, are at full supply level, and a moderate amount of surplus water can be permitted to flow over the top of them when the water in the canal rises.

In other cases, an escape in the form of a canal weir such as shown in Plates LXVI. and LXVII. is used, in which the planks above the weir crest can be removed at pleasure: this form of escape is most suitable when the canal is in embankment. When an escape is constructed simply for scouring purposes, the draw-gate system is preferable to one worked with planks or baulks, and it is desirable to have a drop in the floor of the work, and a free discharge for the water in the escape channel below, so that the flow may not be impeded. When escapes are in the form of clear overfalls, and indeed in other cases too when the channel below the escape runs dry, it is essential that the floor below the outlet

in almost all cases, there is a cushion of water below the escape even when it is first opened. In many cases, large circular basins, the diameter of which is two and three times the width of the channel, have been scoured out below the old works; these pools or *bayarahs* as they are locally called, are cut out to a great depth in some cases, and threaten the wings by their side action, and the floors by their depth. In these old works the floors, and the pitching below the floors, was usually horizontal; the latest practice, as shown in the Abutig escape, is to construct these works with a long sloping masonry talus, commencing generally from the lower curtain wall, but sometimes from the piers, having a crest slope of 1 in 10; and to carry a dwarf wall along the side of the channel, which takes off from the wings, running parallel to the centre line of the channel. This wall has been found to have a very good effect in directing the flow of the water, and in preventing the action on the sides of the channel; the height of it need only be from one-third to one-half the depth of water, but the slope above it must be strongly pitched. In place of this dwarf wall the majority of the engineers in Egypt prefer to construct a dry rubble spur with a masonry footing only. This is much less expensive than the dwarf wall, and has the advantage that as it is less rigid it gives way to any settlement which may occur. A very similar plan has been adopted on the Eastern Jumna Canal, in the Punjab, on a small scale, to stop the pooling below distributary falls; but the dwarf walls are kept above water-line at the wings, and the crests slope at an inclination of one in five, and the slope is carried right down to the bed level at the end of the wall. The rule in these cases is to make the length of the wall from five to six times the depth of the water. The experience of Egyptian regulators and escapes shows that spreading wings, or wings opening from the side walls in a curve, are a mistake, and that the best methods for stopping erosion on the sides and bed are, first, by giving depth and not width to the channel; and, secondly, by forcing the water, and more particularly the lower strata of the stream, to follow a course parallel to the centre line of the channel which lies below the work. In more than one case pooling which threatened to destroy a regulator has been stopped by rough rubble spurs laid in the position taken by the dwarf wall in the plan of the Abutig escape.

The Qushesha escape, shown in plan and section in Fig. II., Plate LXIV., and in perspective in part ii. of the same plate, is a magnificent work capable of discharging 80,000 cubic feet a second. It was designed by Col. Western, R.E., and was completed in 1891. It has

60 vents of three metres (ten feet nearly) each. The maximum head on it is calculated to be about 4·25 metres (14¾ feet), and it may be necessary to open the entire escape when there is this difference of level. There are two lines of gates: the lower line consists of draw-gates, similar in design to those used on the under-sluices of the canals in Upper India (page 176); the upper ones are falling gates hinged at the lower edge. Both are of iron. The lower gates are 2½ metres (8 feet 3 inches nearly) and the upper ones 3½ metres (11 feet 3 inches) in height. The lower gates will be used at times to admit the waters of the Nile during the early days of flood, into the basin above the escape, and also to drain off the water when the Nile is falling. The upper gates are for escape only. Two travelling cranes run on the top of the piers, which are used to raise the upper or falling gates and to lift and lower the draw-gates. The upper gates fall into a water cushion formed by the ashlar sill laid at the lower extremity of the upper floor. These gates have cast-iron quoins and cast-iron bearing plates on the piers, and the grooves for the lower gates are also of cast iron. Each upper gate is retained



FALLING GATES OF THE QUSHESHA ESCAPE IN MIDDLE EGYPT.

against a head of water by two chains anchored to the piers, which are coupled into a simple let-go gear on the centre of the gate, so that both chains can be simultaneously released when it is necessary to open the gates.* These chains are only for use when it may be necessary to allow the gates to fall. When this is not the case, each falling gate is retained

* This sketch is taken, by the kind permission of Major R. H. Brown, R.E., from his paper on the Qushesha Escape, in the 'Professional Papers of the Corps of Royal Engineers, 1892.'

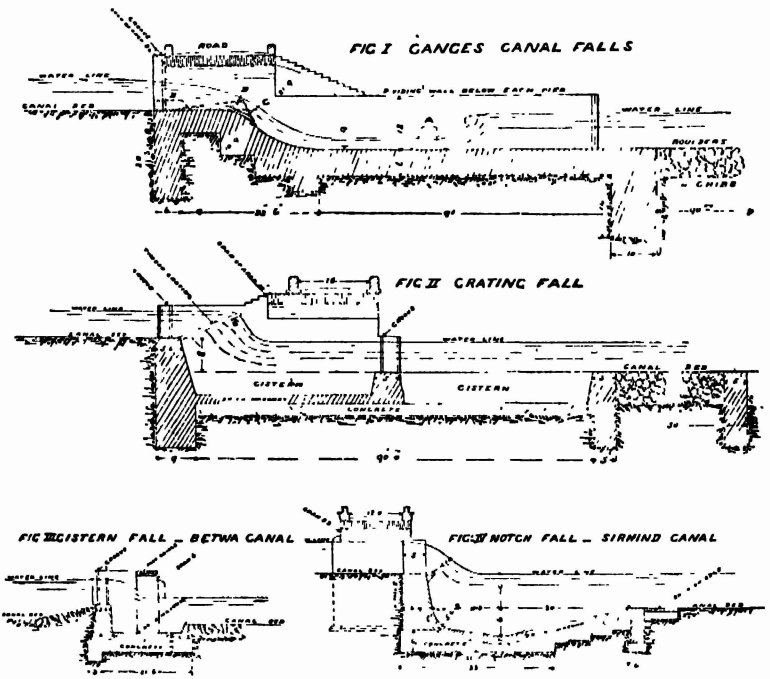
by two wrought-iron rods, one on each side, anchored to the pier and hooked into eye-bolts at the two extremities of the gate; these rods are in two parts, but connected by a coupling which screws to one part with a right-handed screw and to the other part with a left-handed one. By the manipulation of this coupling the gate is pressed, with sufficient tightness, against the vertical cast-iron face. It is easy to transfer the strain from the rods to the chains by putting the latter in place and slackening the couplings. This Qushesha escape drains a total area of 556,000 acres or about 860 square miles of "basins." It is necessary to discharge from 40,000 to 60,000 cubic feet per second under ordinary circumstances through this work, and the discharge may reach 80,000 cubic feet. The vents were divided into two parts, so that, when the river was exceptionally low, the scour on the floor below might be moderated. The upper row of vents above are capable of carrying from 40,000 to 60,000 cubic feet a second with a low river, and the upper and lower vents together will carry a larger quantity. The calculations of the discharging capacity of this great escape are somewhat elaborate, as the discharge from it is so great that it affects the flood level of the Nile in a marked manner; a discharge of 60,000 cubic feet a second will raise the river by about 2¼ feet when it stands at reduced level 25·00 metres above datum. In 1884 the discharge from the area drained through this escape raised the level of the Nile 4½ feet at Cairo, which is 50 miles below Qushesha.

This immense escape was opened for the drainage of the basin system for the first time on the 17th of October, 1891. For a short time previously 32 of the lower gates had been raised about 2¼ feet, to regulate the level in the Qushesha basin: on the date mentioned all of the 60 upper gates were released,* within a period of 20 minutes, by four parties of 3 men each, without a hitch. The whole number could have been released in 10 minutes, but an interval was allowed in order that the spectators who had gathered to see the operation might alter their positions.

Canal weirs or falls are required at intervals on any canal in which the slope of the bed is less than that of the country in which it runs; for as the bed gains on the surface of the ground the water level becomes raised above it until a point is reached at which it is desirable to drop the water over a weir or fall and to commence a new reach of the canal. In canals which are designed for navigation as well as irrigation, a lock

* 'The Qushesha Basin Escape, Middle Egypt,' by Major R. H. Brown, R.E. Professional Papers of the Corps of Royal Engineers.

has to be constructed at each fall. The following sketches show some of the various forms of canal falls which have been adopted: the earliest ones in Upper India were those on the Bari Doab Canal. In the upper reaches rapids were generally adopted, and in the lower reaches, where



SECTIONS OF CANAL FALLS.

boulders were not so readily obtainable, vertical falls (Fig. II.) were generally used, and a cistern was sunk below the level of the lower canal bed to form a cushion of water to resist the shock of the falling stream. On many of the canal falls in Upper India it used to be the practice to fix gratings, as shown in Fig. II., just at the level of the weir crest, sloping up to the surface of the stream: these gratings were composed of timber beams, 4 to 5 inches thick, spaced 6 or 8 inches apart; lying in the direction of the current so that the water was divided into a number of filaments. They still survive in some of the old weirs on the Ganges and Bari Doab canals, but the principle is not a good one. On the Ganges canals nearly all the falls were originally built on what is called the "ogee" shape, with the idea of delivering the water at the foot of the fall without any shock on the floor. The crests of these falls were at the upper canal bed level and were usually of the full width of the canal and sometimes even wider: when a large discharge was passing down the

canal the effect was to increase the velocity in it and to decrease the depth of water for a considerable distance above the fall, so that the velocity of approach at the weir crest was great. The velocity increased of course as the water ran down the "ogee," and the friction on the slope was enormous; the shock on the floor was reduced, but the friction did as much damage as the shock would have caused, and the velocity was so great, that a standing wave was created below the fall, and the washing of the banks was considerable.* These "ogee" falls have given endless trouble: they were constructed in brick and the lower slopes were constantly torn up: ashlar was substituted in some cases at considerable expense. One plan which was first tried was to build cross walls as at A. These walls were swept away over and over again: they were built of all kinds of materials: one, which was standing a few years ago (and may be still), was built of old cannon balls! Another plan was to build up the crest wall, as at B, in conjunction with the wall A. Then the "ogee" was converted into a clear overfall by the addition of a piece of masonry, as at C. In some cases the crest was raised, as at D: this was found to be the best plan of all, and the result was a near approach to the clear overfalls of Figs. II., III., and IV.

On the Bari Doab Canal, which has a rapid slope and high velocity, especially in the upper reaches in the boulder formation, many of the drops of the canal bed are effected by rapids. Plate LXV. shows the style of work. One of the most striking of these is the one called the Cascade Fall: it looks extremely pretty, the water appears to pile itself up in great rolls of fluid as it rises up to the crest of each succeeding drop. It will be noticed that below each drop there is a flat length and then a rising length of floor: the velocity below the drop, on the flat, is greater than on the rise, and a standing wave is produced which seems to endeavour to return upstream as it rolls up to and over the drop. The first 12 miles of this canal has 19 falls and rapids, in addition to a slope of bed of 1 in 1250; the banks are well wooded and the channel winds sufficiently to give variety: the velocity in the canal, which is only 4 to 5½ feet deep, is from 4½ to 5½ feet per second, and the water is usually clear and bright. The Cascade Rapid is altogether 320 feet in length, the dry boulder pitching below the masonry flooring being nearly 160 feet long, and could only have been economically constructed where stone was very cheap. The wings on either side are parallel to the centre line of the canal for the length of the masonry floor, and then they recede in a curve from the former line and finally slope toward the

* See article 111, page 502, Unwin's 'Hydraulics.'

centre of the canal with the object of diverting the current from the banks. It is now held that converging wings below falls are a mistake and that either parallel wings or those diverging slightly are preferable. The rapids on the higher reaches of this canal are all built with piers and grooves for planks, but these are seldom used. Light concrete arches are, in many cases, thrown across from pier to pier to form foot bridges. The ordinary rapids are formed of crates and boulders: there are longitudinal as well as cross rows of crates, and in the larger rapids these longitudinal and cross walls were originally laid in masonry, the square openings between them being packed with boulders 12 inches or 15 inches in diameter, but, when the canal was remodelled, the hand-packed boulders were removed and laid in mortar or in concrete.

In Southern India the practice was always in favour of maintaining a steady velocity in the canal up to the fall by raising the crest and reducing the width of it to that which was necessary for the purpose. This plan caused, of course, a somewhat greater drop than was obtained where the crest was at the canal bed level, and the width of it equal to or even greater than that of the canal; but the velocity of approach was less, and the action on the floor below was moderate. Plate LXVI. shows a typical Madras fall, with a depressed floor or cistern below, but in many cases, the floor is at the level of the canal bed below the fall; the Madras type has been generally followed in Bengal, but the arrangement of the screw shutter shown on the plate has not been followed. Plate LXVII. shows a canal fall on the Midnapore Canal: those in Orissa and on the Sone are of the same description. In Bengal the custom is to have cast-iron brackets bolted to the crest of the fall with grooves for planks, but in Madras, although this system is employed, there are often draw-shutters lifted by screws from above as in Plate LXVI. When planks are used, they are all kept to a uniform width, so that the discharge of the fall can be ascertained by reading the gauge above the weir and counting the number of planks in each bay. Tables are usually drawn up, and kept at each weir, showing the discharge at varying levels when different numbers of planks are in place. A light bridge over the fall enables the attendants to get at the planks, which are lifted by chains which can be attached to hooks on the planks.

In canals where navigation is allowed it is often necessary, when a very small discharge is passing, to impound the water in the reaches by boarding up the falls above the level at which the canal runs when carrying full supply, and to reduce the water in the reaches almost (or it may be quite) to a horizontal plane. In these cases it is best to

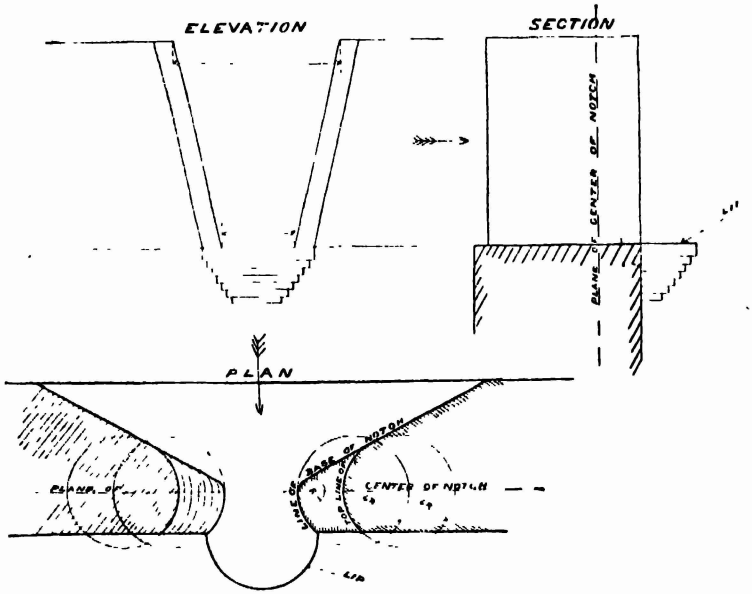
raise the crest of the fall and widen it (suitably for the full discharge) so that the depth on the crest may not be unduly increased. There is always the danger that the men will impound the water and then suddenly open the weir (perhaps to flush down a boat stuck in the shallow water below) and thus throw an excessive strain on the lower floor. It is usually considered in Bengal that 3 feet 6 inches to 4 feet is a sufficient depth of water on the crest of a fall when it has to be regulated by boards.

When the discharge of a canal is fairly constant there is no necessity to impound the water in the reaches for navigation; and in canals where navigation is not practised, it is never necessary to do so. In these cases there are very great advantages in adopting the form of canal fall which has been so successful on the Sirhind Canal in the Punjab. In this design the difficulties of excessive velocity and great action below the fall have been overcome. Plate LXVIII. shows a lock and fall on the Sirhind Canal, and Fig. IV. on page 192 gives a section through the breast wall of one of these falls. Plate LXIX. is a typical design of the notch falls which have been constructed on the Chenab Canal in the Punjab. The breast wall of the fall is cut into a number of notches of which the bases are at the canal bed level, the crest of the breast wall being above full supply level; at the foot of each notch there is a lip projecting beyond the lower face of the breast wall, which has a great influence in spreading the stream and determining the form of the lower face of the falling water. The notches in the wall are all alike and they are so designed that they discharge at any given level the same amount of water approximately as the canal above carries at that level, so that there is no increase in velocity in the canal as the water approaches the fall,* but a uniform flow and a uniform depth is maintained. These notches work most sweetly. The water flows from them in a fan-like shape and meets the water surface below with a steady flow which contrasts most favourably with the violent ebullitions which accompany all other clear overfalls, and there is no vestige of the standing wave which is produced in falls which permit of a greatly increased horizontal velocity. The action on the canal banks below these falls is very small although the wings are of very moderate length. There is no question of the superiority of them over all others where the circumstances admit of their being adopted. They are universally used throughout all the distributaries of the Sirhind Canal, where no heading-up of the water by planks at the falls (which is so common in Bengal and Orissa) is

* Except for a few feet close to the notch.

permitted. It will be noticed from Fig. IV., page 192, that the form of the floor below the fall is peculiar; it has great depth immediately below the point where the greatest shock from the falling water has to be received, and it slopes up from that point to the level of the canal bed. This form is peculiarly suitable for checking the ebullitions of the water and reducing it to steady forward velocity, and is based on the same principle as that on which the form of floor below Egyptian regulators and escapes has been determined (page 189). At the end of the floor the water flows almost quietly into the canal. There is hardly any pitching required on the canal bed below the floor. The rising floor was adopted in Madras for canal falls before it was introduced in Upper India, but the curved form of the toe of the breast wall and the position of the deepest point below the point of maximum impact is peculiar to the Punjab.

Although this form of fall is very good, the depth of the foundations adds considerably to the difficulty of construction, except when the soil is very hard. In many cases, especially where ashlar is not very expensive, it may be cheaper to protect the floor by mere strength of materials than by the deep cushion which this form of section affords.

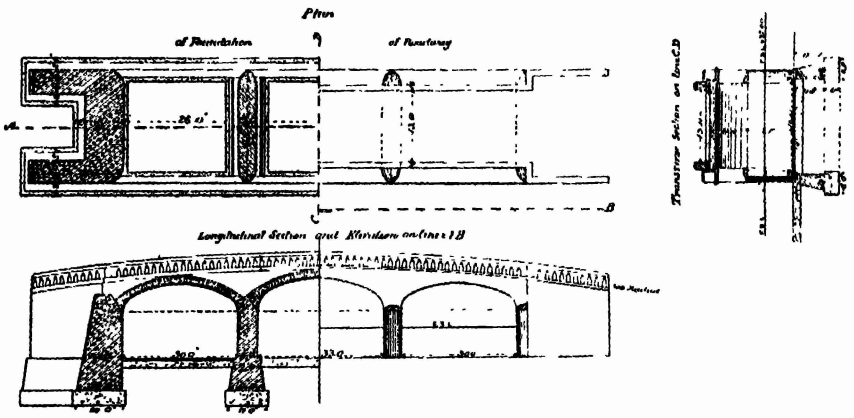


FORM OF NOTCH USED IN FALLS IN THE PUNJAB.

A series of experiments on the best form of notch was carried out by Mr. Benton: he showed from theoretical considerations that the form

of notch which would discharge with absolute accuracy the quantity of water carried by a trapezoidal channel with any depth of water in it, was one with a curved base and sides of a certain form, but he proved that a trapezoidal notch might be made which would be quite sufficiently accurate for all practical purposes. The formulæ which were adopted are given in Appendix X. The form of notch which was approved is shown in the sketch on the previous page.

Bridges over Indian canals vary very widely in design. Of late years iron bridges with wooden roadways have been more largely used, but they are very expensive in repairs. The sketch below shows a common type of bridge in Madras.



CANAL BRIDGE IN MADRAS.

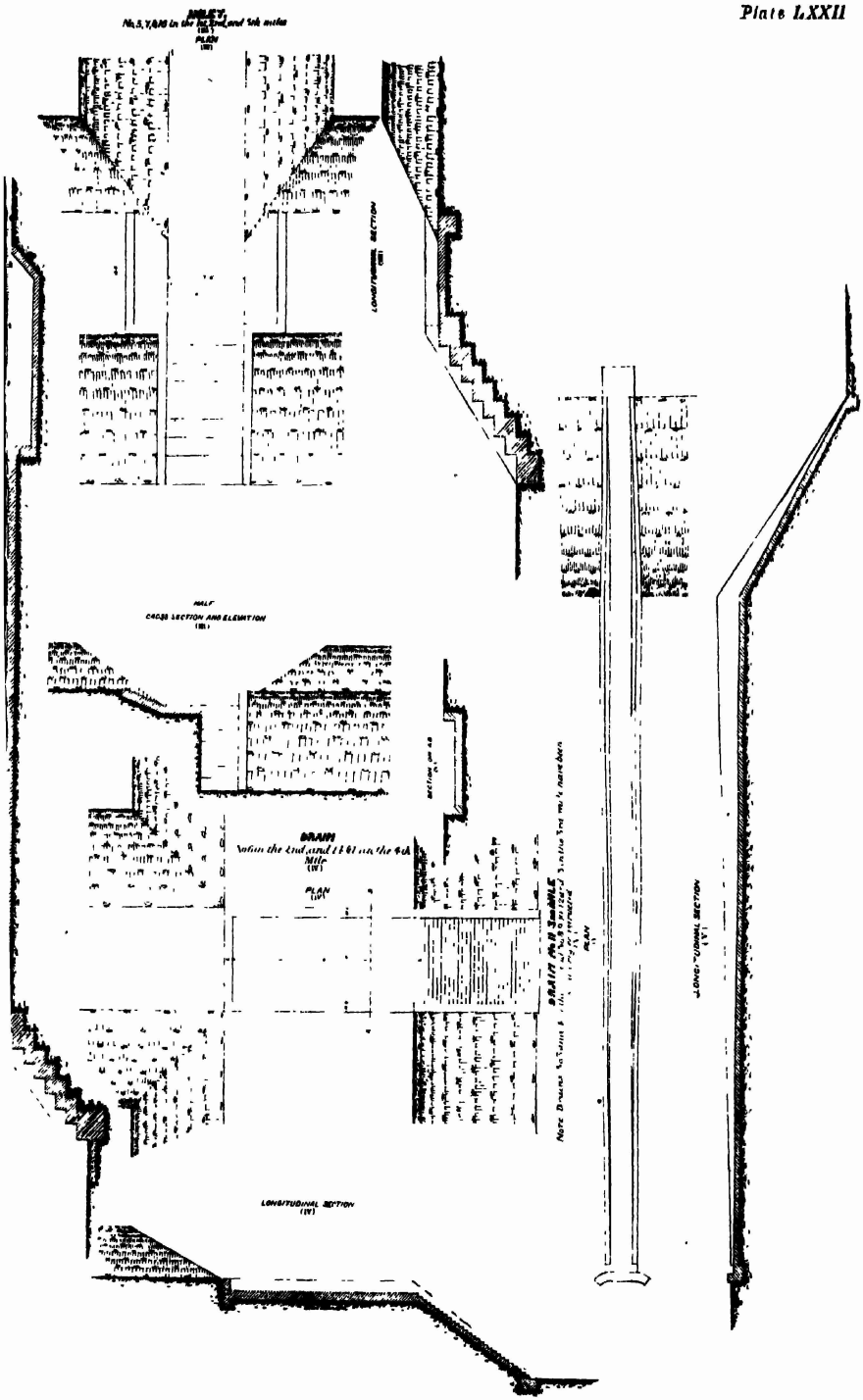
Plates LXX. and LXXI. are fairly typical cases of bridges in Bengal and the Punjab. As a rule it is not desirable to restrict the waterway of a canal or distributary at the site of a bridge by more than 30 per cent., owing to the various disadvantages due to any alteration in the velocity of flow of the water. In navigable canals in Bengal a headway of 15 or 16 feet is necessary to provide for the easy passage of the majority of native boats.

CHAPTER XIII.

CROSS DRAINAGE WORKS, SUPER-PASSAGES, AQUEDUCTS.

Drainage crossing Canals—Inlets and Escapes—Rutmoo Torrent, Ganges Canal—Danger of Canal being blocked—Budki Super-passage—Siswan Super-passage—Solani and Kali Nadi Aqueducts—Aqueducts in Bengal—Syphon Aqueducts—Velocities in Syphons—Difficulties connected with Syphons in Flat Drainages.

AN irrigation canal is best placed, of course, when it runs on the crest of a ridge, and when the drainage off the neighbouring country flows from it on either side. Such an ideal position, however, is rarely attained by any canal during the whole of its course, except perhaps in some cases in deltaic systems, and usually it is necessary to carry the alignment of a canal across one or more drainages or streams before it can be laid down on the ridge. This is more particularly the case when a canal is compelled to run on a contour at the foot of hilly ground —as frequently occurs with the upper canal in a deltaic system, and almost always with canals leading from reservoirs—when drainages must necessarily cross it at right angles; or, when a canal takes off the higher portions of a river in the neighbourhood of the hills, where it is not so easy to divert the drainages and streams as it is in the easier gradients of the plains. The cost of the works necessitated by cross drainages is often considerable, and in some cases—as in the Ganges and Sirhind canals—it may exceed the cost of the head-works themselves. Cross drainages, when the volume of water concerned is small, may be admitted into a canal and absorbed in it; examples of inlets suitable for this purpose are illustrated in Plate LXXII. But when the volume is too large to be treated in this manner, the discharge of the cross drainage must be passed, either (1) through the canal by inlets and escapes, or (2) over it by super-passages, or (3) under it by syphons, culverts, or aqueducts. The system to be adopted depends mainly on the relative levels of the beds of the canal and drainage, and partly on the relative cost of the different systems: when the bed of the


PLAN
LONGITUDINAL SECTION
HALF
CROSS SECTION AND ELEVATION
PLAN
LONGITUDINAL SECTION
PLAN
LONGITUDINAL SECTION

drainage is at the same level as that of the canal or slightly above it, it is generally cheaper to pass the discharge through the canal by means of an inlet on one bank and an escape on the other, than to carry it under the canal in syphon. If the bed of the drainage is above that of the canal, a super-passage is generally cheaper, and more secure, than a syphon. If the bed of the drainage is below that of the canal, it is generally better—and of course, essential, if the canal is navigable—to carry the drainage under the canal, through a syphon or aqueduct, than to place the canal in syphon under the drainage.

In dealing with all questions of cross drainages, the first point which has to be considered is the maximum discharge which has to be carried across the canal. In Chapter IV., the question of maximum flow-off from catchments has been treated, and statistics have been given which help to determine the probable discharge from any given area ; but it is better, when it is possible, to rely on gauged discharges of actual floods rather than on any estimate based on the area drained.

The Orissa Coast canal, which is a canal for navigation only, in Bengal, crosses heavy drainages and spills, which attain to more than 40,000 cubic feet a second in some cases : it affords a good example of the manner in which such drainage may be passed through a canal by inlets and outlets (or escapes) in the banks when the drainages are broad and shallow. Plate LXXIII. shows the system of construction which was employed ; the length of the work was, of course, varied with the volume to be discharged : the particular case shown is one of a small drainage, and the outlet was designed so that the canal could be supplied through it from a tidal stream below.

The Rutmoo torrent, which crosses the Ganges Canal at a point where the bed of the torrent and that of the canal are at about the same level, carries some 35,000 cubic feet a second, and has a bed slope, near the canal, of over 8 feet a mile. There is an inlet and an escape opposite each other on either bank of the canal, and a regulating bridge in the canal itself below the crossing, so that, when there is a flood in the Rutmoo, the discharge of the canal can be regulated at will, and is not affected by the discharge of the torrent. The inlet and escape consist essentially of a floor at canal bed level with piers dividing the opening into bays which can be closed by shutters. The intention originally was to close up the vents in the inlet to prevent the water standing up the bed of the Rutmoo, and arrangements were made for draining off any leakage ; but in practice this is not done, but the canal water remains impounded in the depressed channel of the stream when there

is no discharge in the torrent, so that the inlet might have been omitted altogether. The outlet is fitted with falling gates, hinged at the lower edge, which can be let go easily when a sudden flood comes down the Rutmoo, and there are grooves for "kurries," or horizontal baulks, in front of the falling gates. The fall of the bed of the torrent below the canal is rapid, and a retrogression of levels in the bed, which would have been dangerous to the canal, is checked by a series of five weirs, or bars of masonry, each having a drop of 4 or 5 feet, which are placed at intervals of 200 feet or so from each other. In several cases, streams which cross the Eastern and Western Jumna canals are taken through the channels in a somewhat similar manner.

In these cases there is not infrequently some danger of the canal being blocked up by the detritus carried forward and deposited by these hill streams. The action of hill torrents in eroding one portion of their beds, and in raising other portions by pushing forward fan-like terraces of deposits, is well known,* and is very similar to the action of larger rivers in forming deltas at their junction with the sea. A torrent descends in a bed which, in the hills and near the foot of them, may have a fall as great as 40 feet or 60 feet in the mile; in this portion of its course it will be constantly eroding its bed by cutting back and increasing the slope until the action is stopped by rock; the velocity will be great, and the eroded matter, whether boulders, shingle, sand, or mud, will be carried forward in the stream. Further from the hills the slope of the stream becomes reduced, and it will spread out over the plain and deposit fan-shaped layers of shingle or sand, which, in the course of years, block its passage, and compel it to take a course to the right or left of the one it has previously followed. A similar process goes on in this new course, and the country is raised gradually by a system of incremental deposits, which ultimately so seriously impede the discharge of the stream, that, on the occasion probably of an unusually heavy flood, it forces a passage through the ground it has itself raised, and, cutting a channel through its own deposits, it carries forward the shingle and sand to the lower ground below, which it then attacks in the same manner. If it so happens that a canal is carried through the zone in which a torrent is raising the surrounding land, the deposits may seriously affect any work which may be constructed to pass the torrent across the canal. Such a case has occurred on the Ganges Canal, where the Puttri torrent has been carried over it in a

* And is fully described in Chapter II. of Sir Proby Cautley's Book, on the Ganges Canal.

super-passage. The crossing is about 6½ miles from the foot of the hills, where the slope of the stream is about 25 feet a mile; since the super-passage was built the bed of the stream has been raised, by the action just described, some 6 or 8 feet, so that the top of the side walls, which were 10 and 12 feet above the floor of the channel, are now only 5 and 6 feet above the silted bed, and the floods sometimes overtop them. In the case of the Rampoor super-passage—which is another torrent crossing the Ganges Canal—this difficulty has not occurred, for the work is so near the hills that the zone of deposit is beyond the canal. The floor of the super-passage is quite clear of all trifle of silt.

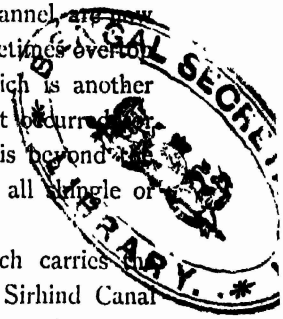


Plate LXXIV. shows the Budki super-passage which carries the joint floods of the Sugh and Budki torrents across the Sirhind Canal at a height of 24 feet above it. These torrents are estimated to carry the following discharges:—

Name of Torrent.	Drainage Area in Square Miles.			Length of the Catchment Basins above the Canal in Miles.	Computed Flood Discharges.		
					By Observations on Floods in Cubic Feet per Second.	Deduced from Rainfall.	
	In the Hills.	In the Plains.	Total.			Discharge in Cubic Feet per Second.	Flow-off Catchment in Inches per Hour.
Sugh .	18	21	39	14	21,504	15,495	0·61
Budki..	12	35	47	17	12,493	13,111	0·45
Total ..	30	56	86	..	33,997	28,606	0·515

The super-passage was designed to carry 30,000 cubic feet per second only,* as it was considered that the discharge ascertained by observation on the surface slope and cross section of the flood, was in excess of the truth. The width of the super-passage between the parapets is 400 feet, and the depth, when carrying 30,000 cubic feet a second, is estimated to be 8·84 feet at the entrance, and 8·4 feet at the outfall. The channel leading to the super-passage consists of a central gullet with an inclination of 1 in 625, which is of sufficient width (540 feet) to carry ordinary floods, but the side banks of the channel are retired 110 feet on either side of this central gullet, so that, in large

* Report, dated 6th of March, 1879, on the Budki Super-passage, by M. T. Higham.

floods there is sufficient waterway to carry the maximum discharge within the limits of the levels fixed for the water surface.

The soil below the foundation of this work consisted of a layer of hard firm clay, about 8 feet thick, overlying sand, which covered a second stratum of blue clay. The concrete foundation, which is entirely boxed in with a curtain wall 8 feet deep below the canal bed, was designed to be 20 feet broad and 5 feet thick under the piers, which was found to be more than sufficient to reduce the pressure on the base to less than 2 tons on the square foot, which was considered a suitable maximum in this case. In the neighbouring case of the Siswan super-passage, which carries a torrent of 20,000 cubic feet a second over the same canal, the nature of the foundation was less favourable, as it consisted of a 10-foot layer of thick tenacious black clay, overlying a fine blue sand of unknown depth, which was of the nature of a quick-sand; being charged with water under a pressure of about 24 feet above the surface of the sand. In this case the super-passage—which is otherwise very similar in design to the Budki one—has inverts turned below the piers to distribute the pressure over the whole area underlying the work. The maximum pressure at the under side of the floor is a little more than 1 ton per square foot.

Where it is necessary to carry the discharge of a torrent, river, or drainage under a canal, the nature of the work depends on the relative levels of the canal and the surface of the water to be passed across it. When the surface level of the latter is below the bed of the canal, an aqueduct is required, and the problem to be dealt with is very similar to that of a super-passage, the only difference being that in an aqueduct the canal flows over the stream or drainage, and in a super-passage, the latter flows over the canal. The Solani aqueduct,* which carries the Ganges canal over the Solani river by 15 arches of 50 feet span, was the largest in India until the Kali Nadi aqueduct was lately constructed on the Lower Ganges canal. The Solani river drains an area of about 216 square miles, and has a flood discharge of about 35,000 cubic feet a second. The extreme width of the foundation of the aqueduct is 252 feet, and the waterway of the aqueduct itself, which carries the canal discharge of about 6500 cubic feet a second, is 172 feet broad; it is divided by a continuous wall along the centre, and piers fitted with grooves are built at each end, so that one half of the aqueduct can be closed for repairs. The parapet walls are 12 feet 9 inches high.

* Which is fully described in Chapter IX. of the second volume of Sir Proby Cautley's Report on the Ganges Canal.

The Kali Nadi aqueduct, Plate LXXV., which is referred to in Chapter IV., page 54, carries the Lower Ganges canal, which at this point has a maximum discharge of 4100 cubic feet a second, over the Kali Nadi, which drains an area of 2377 square miles, and has a maximum discharge of more than 130,000 cubic feet a second. The aqueduct has 15 spans* of 60 feet each, divided by abutment piers into three sets of five spans each; the whole work is founded on wells sunk 50 feet below the bed of the stream. The pressure on the bases of these wells does not exceed 2½ tons on the square foot under the most unfavourable circumstances, and that on the bases of the abutment piers is only about two-thirds of that amount. The circular wells are 20 feet in diameter under the piers and left (canal) wings, 13 feet diameter under the river wings, and 12 feet diameter under the abutments, abutment piers, and right (canal) land wings. The river wing walls run back well beyond the ends of the land wings, to protect the flanks of the work. The main arches are 4·15 feet thick for one-third of their width at the centre, and 4·58 feet at the sides: the load on the main arch is lightened by spandril arches of 4 feet span, with piers 1·7 feet thick. There is one course of bricks laid flat in cement over the spandril arches, and the entire canal floor is covered with a layer of fine cement concrete, and the sides of the channel are plastered in cement in order to make them perfectly water-tight. The width of the channel across the aqueduct is only 130 feet, which causes a velocity of 4 feet a second at times of maximum supply: the bed and sides of the earthen channel, where it is contracted above and below the aqueduct, are strongly revetted with rubble to enable them to stand the velocity.

Plate LXXVI. shows two aqueducts in Bengal, one on the Midnapore, and the other on the Sone canal.

When the surface of the water in the drainage or stream is approximately at the same level as that of the canal, or when it is above the canal surface, it is necessary to pass the drainage (if it must go below the canal) by a syphon aqueduct. Plate LXXVII. shows a work of this kind which carries the flood of the Kao Nullah under the Main Western canal in the Sone system in Bengal. The Nullah, which drains an area of 57 square miles, of which the greater part is in hilly ground, is subject to sudden floods and the discharge was estimated to be equal to a flow-off of 6 inches in 24 hours, or 161 cubic feet per second per square mile, but experience has shown that the

* Note by Colonel J. G. Forbes, R.E., Chief Engineer, N.-W. Provinces.

discharge is not as great. This work, and most others of this class, is subject to the disadvantage that the syphon is liable to be filled up by detritus washed into it during a flood. The result of this may be disastrous. An accident of this kind occurred on the Kistnah canals in Madras,* where a syphon aqueduct, somewhat similar to the one shown on the plate, became filled up by detritus and was entirely swept away: the water of the drainage breaking across the canal. In the case of the Kao syphon the accumulations in it have to be partially cleared out every year.

In all works of this class it is necessary to consider the upward pressure on the covering of the syphon vents due to the head upon them under the most unfavourable conditions, which occur, of course, when there is no water in the upper channel. It may be that the canal will never be dry at the time when a flood occurs in the drainage, but it is usually better to provide for such a case. In the Kao syphon the cover stones of the vents are anchored down to the foundation by wrought-iron bolts.

Plate LXXVIII. shows two cases in which a canal is carried in syphon under a drainage. In the case of the Betwa Canal syphon the ashlar floor is bolted down to the piers. The Nira Canal syphon is peculiar: several of the kind have been constructed on the canal: the barrel of the syphon acts as an arch and so utilises the weight of the abutments to resist the upward pressure of the canal. In these syphons there is rarely any water in the drainage crossing over the canal.

As a matter of economy it is, of course, advantageous to restrict the waterway of a syphon as much as possible, and it is also often desirable to do the same thing in order that a high velocity may prevent silt from being deposited in the barrels.

The capacity of the barrels of a syphon aqueduct is usually designed so that the maximum discharge can be passed at a velocity varying from 5 feet to 8 feet a second, provided that the circumstances permit of a sufficient head being placed on the syphon to generate such a velocity. In syphons with a vertical drop, such as that in Plate LXXVII., which was designed for a velocity of rather over 8 feet a second, the flow of the water approaching the syphon is checked by the vertical drop, and it is necessary to allow ample head to generate the required velocity in the syphon. In most cases a head of at least 30 inches would be required to generate an 8-feet velocity, and it is often difficult to obtain this without going to

* Note by Inspector-General of Irrigation, p. 23, Sone Canal Selection. Bengal, 1890.

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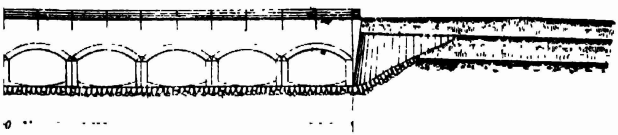
Figs. 1,2.

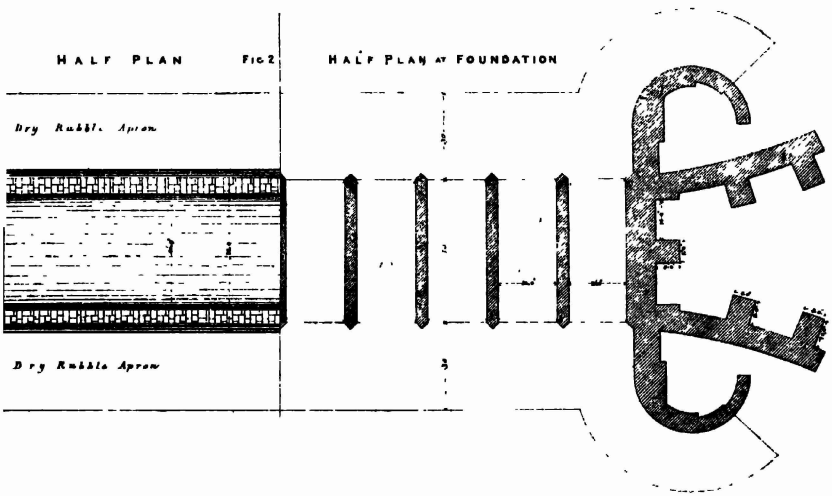
Figs 3,4.

Figs 5,6

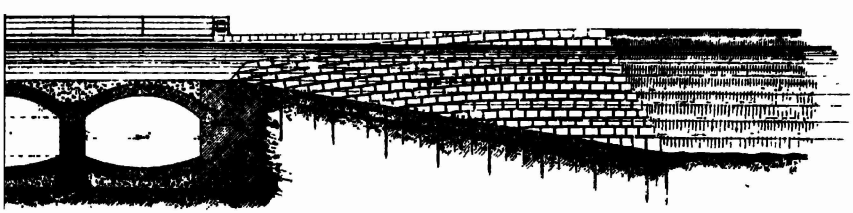
ATION Fig 1



HALF PLAN Fig 2 HALF PLAN AT FOUNDATION



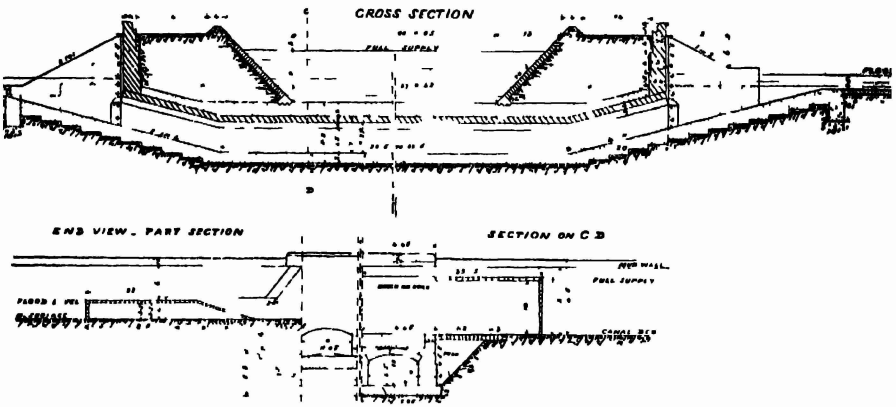
LONGITUDINAL SECTION Fig 4



considerable expense, either in embanking the channel above the syphon or in excavating it below it, and in flat shallow drainages it may be impossible to do either. In the latter case there is no alternative but to increase the waterway of the barrels to such a point that they will be capable of carrying the discharge with the velocity due to the head which can be obtained. In estimating what that head will be, it is necessary to consider the discharging capacity of the channel below the syphon (if there be any defined channel) at different levels, and to compare these levels with those that will obtain in the upper channel when it is carrying corresponding quantities, and to inquire whether the difference between the two is in all cases sufficient to generate a velocity in the syphon which will pass the discharges through the waterway. At first sight it would appear that the water on the upstream side would always accumulate above the syphon until a sufficient head was obtained to pass the discharge (assuming of course that the barrels were proportioned to a reasonable velocity). But in very flat drainages, such as have frequently to be dealt with on smaller canals and distributaries, it is often not practicable, for one thing, to permit of much heading-up, either from fear of damage to crops or houses, or for other reasons, and it will generally be found that, even when such heading-up is feasible, the rise in level on the downstream side, due to the increased discharge, will so far counterbalance the rise on the upstream side that it is not practicable to obtain a head sufficient to generate a velocity which will greatly exceed that of the water above the syphon. In such a case the syphon has to be designed with far greater waterway than is necessary when dealing with a stream or drainage where there is a comparatively rapid slope and good outfall. In all cases of shallow drainages of slight surface slope, shallow and wide vents are preferable to narrow ones of the same waterway, in order that a wide entrance and exit over the lip of the syphon may be obtained for the water entering and leaving it. The sketch given overleaf shows typical sections of the syphons which are being constructed on the Chenab Canal in the Punjab, which are very suitable for cases of this kind.

It must be remembered that in those cases where the drainage water is headed-up by a syphon, and there can be, of course, no overfall over the lip, the velocity over the lip into the well is necessarily no greater than the velocity of approach of the water in the drainage; in such a case the width of the lip must be determined by the maximum depth permissible, and the probable velocity of approach of the water; the width, in shallow drainages, will necessarily bear a larger proportion to the depth,

and it is convenient that the vents should do the same. These considerations are not infrequently overlooked, and syphons are constructed with deep narrow vents and narrow entrances, in which the discharge is



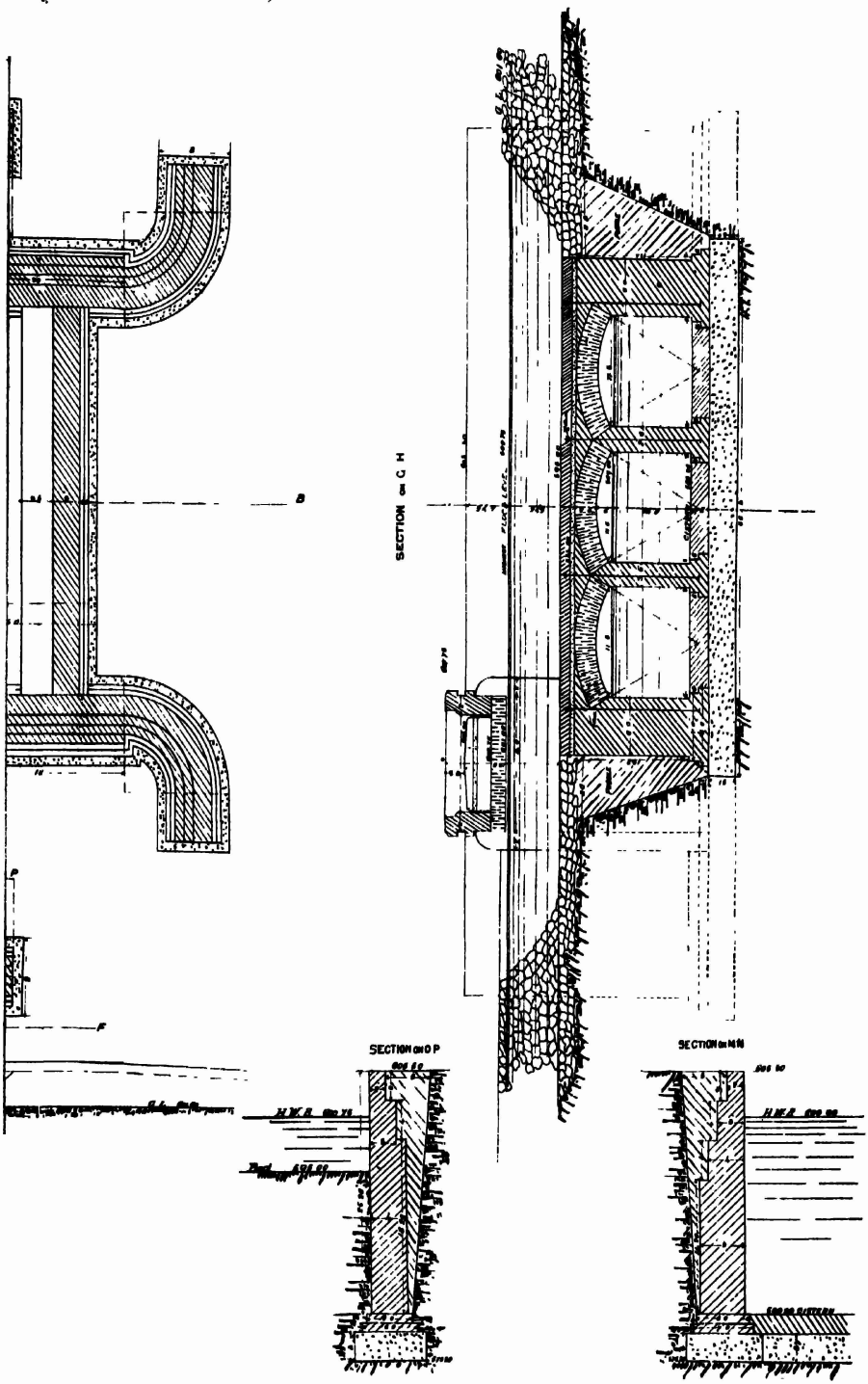
TYPICAL SECTION OF SYPHONS ON THE CHENAB CANAL, PUNJAB.

really determined by the discharge over the lip until the water on the upstream side has headed-up to an extent which seriously floods the country or breaches the canal or distributary concerned.

MAIN CANAL

ssage for Gandhia Drainage

Plate LXXVIII



CHAPTER XIV.

NAVIGATION, LOCKS.

Canals for Navigation only—Silting in Tidal Canals—The Bhangore Khall—Canals for both Irrigation and Navigation—Velocity of Flow in Canals for Navigation—Combined System of Irrigation and Navigation not financially successful—Relative Position of Lock and Weir—Cracking and Failure of Lock Walls—Apjohn's Theory of Settlement of Foundations in the Deltaic Soil of the Ganges—Pressures on Lock Walls—More recent Designs adopted in Bengal—Equality of Pressure on Foundations desirable during Construction—Width of base of Lock Walls—Lock Gates and their Fittings.

THERE are three large canal systems in India which have been constructed solely for the purpose of navigation; these are the Circular and Eastern Canal and the Orissa Coast Canal (including the Tidal Canal) in Bengal,* which are shown on Plates LXXIX. and LXXX., and the Buckingham Canal in Madras (Frontispiece). These systems are not used in any way for irrigation, and could not be so used, as the water in them is generally brackish. The canals are in immediate contact with the tidal creeks and rivers connected with the Bay of Bengal; indeed, the greater portion of the Circular and Eastern Canal, which connects Calcutta and Barrisaul in Eastern Bengal, consists of natural tidal channels which have been artificially improved, and which are maintained in a fairly efficient state in order to bear to Calcutta the products of the eastern and northern districts. The portion of the Orissa Coast Canal which is called the Tidal Canal was opened for traffic in 1869: it connects the Hoogly River with the Russoolpore River by two tidal ranges. The Orissa Coast Canal proper, which is a continuation of the Tidal Canal, was opened for traffic throughout in September 1887; it consists of three ranges connecting the Russoolpore River with the Matai River, in Orissa. The united system is a line of navigable canal

* The Tidal Canal appears separately in the Government statistical returns, as it was constructed from borrowed funds, and the Orissa Coast Canal was not. But these two really form one and the same line of navigation.

which opens inland water communication between Calcutta and Orissa. The Buckingham Canal in Madras, which has some features in common with the Orissa Coast Canal, is also a coast line. It was undertaken primarily as a protective work after the famine of 1877–78, in order to connect the Godaveri and Kistna deltas with the southern districts of the province. Of these three navigable systems, the Calcutta and Eastern Canal, which was in partial operation at the end of the last century, has always paid well, but the others are not financially successful at present. The following statement gives some statistics concerning them :—

CAPITAL COST AND REVENUE DERIVED FROM THE LARGE NAVIGATION SYSTEMS.

Canal.	Estimated cost, direct and indirect charges.	Capital outlay, direct and indirect, to end of 1890-91.	In the year 1890-91.			
			Gross Revenue.	Working expenses, including indirect charges.	Net Revenue.	Percentage on Capital.
	Rx.	Rx.	Rx.	Rx.	Rx.	
Bengal :—						
Circular and Eastern Canal.	..	529,390	52,515	32,402	20,113	3·8
Orissa Coast Canal (including the Tidal Canal).	710,718	638,546	9,367	13,041	−3,674	
Madras :—						
Buckingham Canal..	929,195	768,909	8,802	11,770	−2,968	

The Calcutta and Eastern Canal is in some ways a remarkable work ; it runs through the upper margin of the Soonderbun forests, where the land is generally below the very highest flood level, but has been reclaimed by embankments and is generally cultivated. A little nearer the Bay of Bengal the vast area of swampy land which forms the Soonderbuns is covered with dense maiden forest. It will be seen from Plate LXXIX. that the canal runs generally east and west, while the various channels, or "gongs" as they are locally called, which are

* The symbol Rx. denotes "tens of rupees," that is, the old conventional pound sterling of the days when ten rupees were equal to one pound.

connected with the Bay of Bengal, run generally north and south. These "gongs" are all tidal, up to, and in most cases a considerable distance beyond, the canal itself, so that the general ebb and flow of the tide is more or less at right angles to the line of the canal. The main channels, however, are linked together by an intricate system of cross streams, which intersect the muddy swamps of the Sonderbuns in all directions, so that it is always possible to find a way from one "gong" to another in a direction which is more or less east and west. The canal has, in fact, utilised a connecting system of cross channels between the main "gongs" to a large extent, and in some cases artificial channels have been made. In many of these connecting channels a great difficulty has occurred owing to the tides meeting in them. The tide makes up the main "gongs" on either side of a connecting channel at the same time, and enters the east mouth and the west mouth of the canal channel simultaneously; the result is that the in-flowing tides meet at some point in the channel, and at that point there is no flow. The waters are heavily charged with silt, which is deposited very rapidly where the velocity of the flow is checked; consequently, the canal silts badly at these meeting-points, and heavy expenditure in silt clearance is involved.

The Bhangore khall, Plate LXXXI., near Calcutta, is a case in point: this khall (or channel) is partly artificial and partly natural; it runs from the Kantatollah gong (or river) on the west to the Kooltee gong on the east. These are both deep channels. The bed-levels of them are about 20·00 to 25·00 below M.S.L. at the point where the Bhangore khall joins them. The bed of the Bhangore khall varies from 3·00 + M.S.L. to 10·80—M.S.L. The flood tide flows, as shown by the arrows in the accompanying plan, into the Bhangore khall from these two gongs. The tides meet about the centre of the khall in the 19th and 20th miles. The result of this is, that however frequently the Bhangore khall is excavated, it soon silts up to the section shown in the plate. Silt is deposited at the meeting-point of the tides. At low water about two miles of the channel are dry; at high water the depth in the 18th and 19th miles varies from a maximum of about 5½ feet (on occasions of abnormally high tides) to a minimum of about 2 feet. It may be said that there is generally 3½ to 4½ feet of water available for traffic; this depth only obtains for about 1½ hours at high tide.

In other parts of the vast area subjected to tidal influence in the delta of the Ganges there are other channels which are so situated as to be under conditions somewhat similar to those which have influence on the

Bhangore khall, but which do not degenerate as this khall does. Such channels maintain a fair depth in the centre under two conditions :—

1. When, near the centre of the channel, there is connection with a bheel into which the tide flows and ebbs. The bheel, in this case, acts as a flushing reservoir, and maintains a flow of such a quantity of water past the centre of the channel as is sufficient to maintain a certain section.

2. When, owing to circumstances which it is most difficult to explain, the action of the tides in the large rivers is such that the channel in question becomes what the natives call *chowbatta* (four ebbs). This phenomenon is simply this :—In the twenty-four hours there are four instead of two ebbs, and four instead of two floods, or, to speak more correctly, the first portion of every tide (whether flood or ebb) flows in one direction and the second portion in the opposite direction. This action maintains a good channel, because the flow past the centre is constantly maintained.

The first system fails when the bheel silts up, or is reclaimed ; the second only fails when, owing to change in the tides of the large rivers, the chowbatta tides cease.

There is abundant evidence of the efficiency of the two natural systems by which channels lying between tidal streams are often maintained. If the same systems can be artificially put into action in the Bhangore khall it would seem reasonable to suppose that they would be equally successful there. Some years ago a project was proposed for doing this in the case of the Bhangore khall. It is illustrated in the lower part of Plate LXXXI.

The project is this :—A "circulating channel," A B X C D, is to be excavated. At the points A B C D "stop dams" are to be constructed in such a manner that they can be closed against the tide. The channel A B X C D is to be cut with a base of 40 feet, a bed level of 6·00 — M.S.L. side slopes of 2 to 1. The waterway at the points A B C D is to be approximately the same as that of the existing khall at the points E and F where its bed has the level of 6·00 – M.S.L. The volume of water which will lie in the channel A B X C D between the high and low tide levels is to be approximately the same as the volume which now lies between high and low tide levels above E and F respectively. The channel of the Bhangore khall below A and D respectively is to be excavated in such a manner that the waterway at any point distant x feet from X, shall be approximately the same as the waterway which now exists at a point x feet from the 19th milepost.

The action of the tides will be as follows :—During every flood tide both the stop dams A and D will be open, but at every ebb one or

Plan Register No. 64 I of 1891-92, P. W. D., B.

Sketch Map

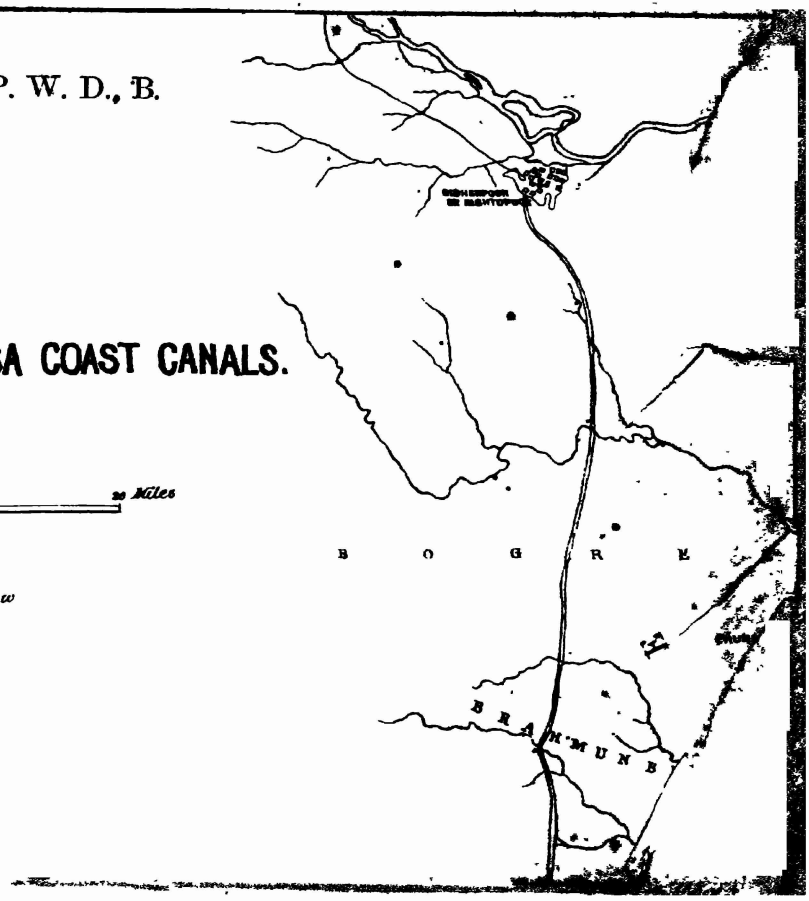
OF THE

MIDNAPORE, HIDGELLEE TIDAL, & ORISSA COAST CANALS.

Scale 4 Inch = 8 Miles.

0 5 0 10 20 Miles

Area commanded ... } Colored Yellow
Do provided with Distributary }
Do. watered in 1890-91 ..... Red



other of them will be closed. The flood will enter through both those stop dams and will fill the "circulating channel." At the first flood tide stop dam B will be closed, and C will be open, the tide will flow from C to X to B; at the top of this tide C will be closed and B will be opened, at the same time stop dam A will be closed, the tide will then ebb from C to X to B to D eastwards, that is, in the same direction that it flowed in the circulating channel. As the next flood makes, stop dam A will be opened (C remaining closed and B open), the flood from A and D will flow past B to X to C; at the top of this flood D and B will be closed and C opened, and the next ebb will pass from B to X to C to A westwards. The result of this action will be that the water in the circulating channel at high-tide will undergo no change in the direction of its flow. It will never have to stop entirely and return. It is at the period of actual stillness that the maximum amount of silt is deposited. The results obtained in *chowbatta* khalls—where the tide is always slack, but where the period of actual stillness is small—appear to show that a comparatively small velocity will have a most powerful effect in preventing silt. The circulating channel is proposed to be six miles long. By the time that the top of the tide has passed round to the stop dam B, the water in the Bhangore khall itself will have commenced to ebb, and it is quite possible that the momentum of the water circulating in C X B will maintain, at high water, such a velocity as will materially hinder deposit of silt. At low water the direction of the flow in the circulating channel will be changed, and it will be at that time only, when there is the minimum depth to deposit silt, that there will be absolute stillness in a portion of the circulating channel.

The discharges which would obtain at the different parts of the system were worked out on the basis of the average tide levels, and were found to be as follows:—

	First flood.	First ebb.	Second flood.	Second ebb.
	cub. ft.	cub. ft.	cub. ft.	cub. ft.
Section 38	36,100,000	17,200,000	36,100,000	45,500,000
„ 53	25,600,000	16,200,000	25,600,000	35,000,000
Stop dam A ..	9,400,000	Nil.	9,400,000	18,800,000
„ C	16,000,000	Nil.	Nil.	16,000,000
Point X	8,000,000	8,000,000	8,000,000	8,000,000
Stop dam B ..	Nil.	16,000,000	16,000,000	Nil.
„ D	9,400,000	18,800,000	9,400,000	Nil.

In the existing channel, experience has shown that a discharge of 8,000,000 cubic feet at each tide is sufficient to secure a waterway of about 400 square feet below 6·00 + M.S.L., so that it is reasonable to suppose that the waterway maintained at the point X would be about the same. This would ensure larger waterway at the important points A D, where the boats pass. This project has not yet been carried out; it is described here as a possible solution of a very difficult problem in the navigation of these channels.

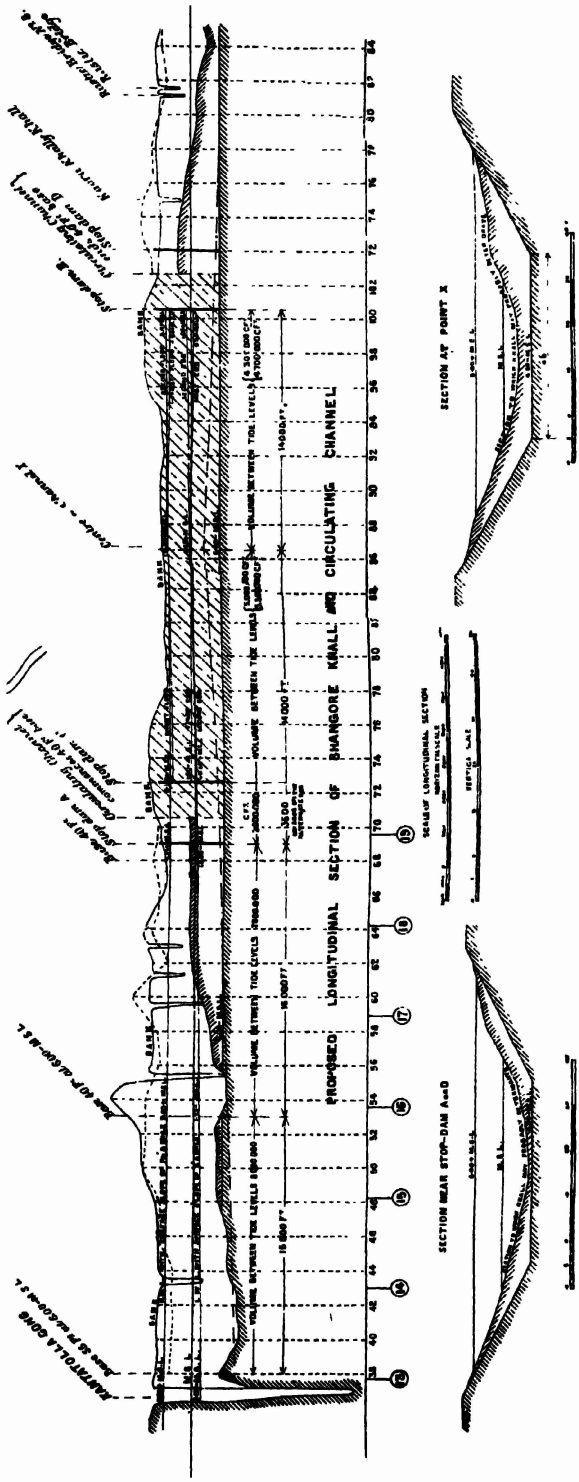
Out of the twenty-two large canal systems in the three Upper Provinces of India and in Madras, which were primarily constructed for irrigation, eleven are also adapted, in certain portions of their channels, for navigation also. None of the canals in Bombay or Sind have been constructed so as to be available for navigation, although small boats are sometimes used on parts of them. The mileage of irrigation canals which are navigable also is shown in the marginal statement. It has been maintained that it is desirable, if not necessary, to make the trunk lines of an irrigation system navigable, in order that an easy and cheap means of carriage may be available for exporting the surplus grains and other products which irrigation produces; it has been further argued that the expense of the additional works necessary is not large, while the convenience to the people and to the officers in charge of the canals is very great. It is by no means easy to estimate correctly the difference in cost between an irrigation canal of a given capacity, and one of the same capacity which is suitable for navigation; the difference is by no means represented by the cost of the locks which have to be added at the canal falls.

Province.	Mileage of Irrigation Canals.	Mileage which is navigable.
Bengal	710	467 (*a*)
N.-W. Provinces	1420	512 (*b*)
Punjab	4058	432 (*c*)
Madras	3143	970 (*d*)

(*a*.) The Orissa, Sone, and Midnapore Canals.
(*b*.) The Ganges, Lower Ganges, and Agra Canals.
(*c*.) The Western Jumna and Sirhind Canals.
(*d*.) The Godaveri, Kistna, and Kurnool Canals.

There are several other causes which increase the cost. In the first place it may be necessary to restrict the velocity of the water below that which the soil will stand, for a velocity of more than 2 feet a second will perceptibly check the traffic, and this necessitates a larger channel and more frequent falls in the canal bed. In Madras, indeed, a velocity of 1·50 to 1·75 feet per second is considered to be the highest allowable under ordinary circumstances in a canal which is used for navigation.

Plate **LXXXI**

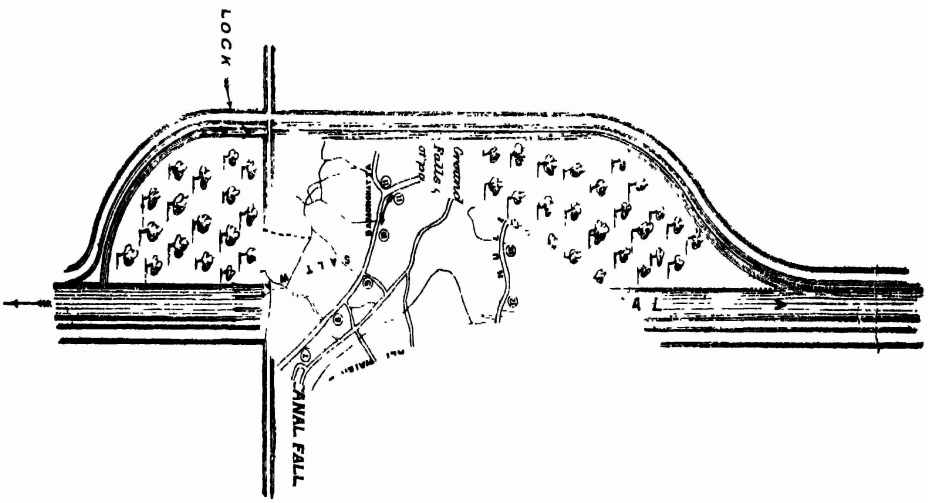

PROPOSED LONGITUDINAL SECTION OF SHANGORE KHALL AND CIRCULATING CHANNEL
SECTION AT POINT X
SECTION NEAR STOP-DAM A and D
SCALE OF LONGITUDINAL SECTION
VOLUME BETWEEN TIDE LEVELS
KANTATOLLA GONG

Then, as it is often necessary to impound the water in canal reaches at times of low discharge in the canal, it becomes necessary to increase the height of the banks and the height of the masonry works near the end of each reach; and again, a navigable canal cannot be reduced in width in accordance with the discharge required for irrigation, so it is often necessary to make the canal in its lower reaches much wider than is required for the purposes of irrigation only: and, further, as frequent locks are to be avoided, in consequence of the impediment they offer to traffic, the reaches are lengthened as much as possible in a navigable canal and the cutting below locks and embankment above them is greatly in excess of that which would be necessary in a channel designed for irrigation only. The height of all bridges has to be greatly increased, with the consequent expense of long approaches to them. A certain quantity of water is consumed in passing the boats through locks, which is consequently lost for irrigation if the canal finally tails into a navigable river; this is a disadvantage which may be of some moment when the supply in the hot weather is scanty and very valuable for sugar-cane crops. As a matter of fact, it cannot be said that the combination of navigation with irrigation has been successful in India; the traffic has always proved to be far less than the projectors of the works anticipated, and the revenu[illegible] om tolls, except in Bengal, is insufficient—or but bar[illegible] over the charges for establishment and maint[illegible] balance to cover interest on the capital co[illegible] ion. When the principl[illegible] d [illegible] n suitable for nav[illegible] ults were anticipated. Thus, [illegible] of the Ganges Canal, which was [illegible] as a work of communication, too, there [illegible] will be of incalculable value. Such a ma[illegible] ing through a most populous and fertile country * * * will, if I mistake not, be the most important work yet executed or commenced in India," and he made a calculation tending to show that the navigation of this canal would lead to an economy in carriage of a very large sum annually. As a fact, however, the amount of goods carried on the Ganges is very small, and tolls received are insufficient to cover the expenditure incurred on account of navigation. The canals in which navigation has been most successfully combined with irrigation are the Godaveri system in Madras and the Orissa and Midnapore systems in Bengal. On

* 'Public Works in India,' by Lieut.-Col. Cotton, Madras, 1854, page 114.

these, as well as on the Sone canals in Bengal, regular steamers are plying for traffic. One of the chief reasons, no doubt, why water-carriage has not been generally successful in India is because canals primarily designed for irrigation do not connect centres of trade, but run on lines suitable for irrigating the land; another reason of the small receipts is probably to be found in the fact that in a highly cultivated district large numbers of draught cattle are required for ploughing, which, at odd times, are available for carting the surplus crops to market at a very nominal cost to the owners.

Plate LXVII. page 194, shows one system of placing the lock and canal fall at a point where a drop occurs in the canal bed. In that case the channel carrying the irrigation supply is diverted to the fall or weir, and the lock is placed on the centre line of the main canal; this is the system usually followed in Southern India and Bengal. On the Ganges canal exactly the opposite procedure was adopted, as shown in this sketch :—



SITUATION OF LOCK AND FALL ON THE GANGES CANAL.

the lock being placed on the side channel and the main canal being carried straight through on its true alignment over the fall. This system is preferable in those cases where the discharge is very large, but a lock channel of so great a length is open to serious objection where there is much silt in the water, for in that case, it rapidly fills up with deposit. On the Sirhind canal the locks and falls, Plate LXVIII., are built together, as is commonly done in France; this system keeps the lock channel clear of silt, but it is objectionable, especially where there are large unwieldy boats to deal with, on account of the difficulty in

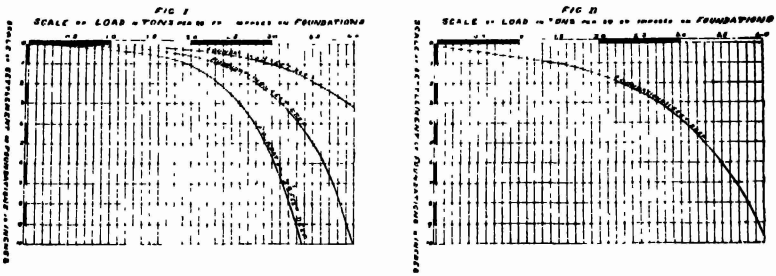
getting the vessels into the lock, the stream to the weir produces a current across the mouth of the lock, and boats cannot easily be kept in their proper course, but are liable either to be drawn into the weir channel or to run with some shock against the lock walls.

Plate LXXXII. gives the plans of locks, designed by Mr. J. H. Apjohn, which have been recently constructed in Lower Bengal. It is not an uncommon occurrence that locks crack longitudinally down the centre of the chamber. In Lower Bengal this defect has frequently occurred, indeed all the locks on the Hidgellee Tidal Canal cracked in this way. The soil in the delta of the Ganges river is of a very treacherous nature; the upper crust for a depth perhaps of 8 to 12 feet is sometimes light-coloured and loamy, but the lower soil is a bluish-black clay, which, when thoroughly dry, cakes hard, and cracks a good deal by contraction, but when wet is slimy and liable to sudden slips. This silt will sometimes stand in canal banks for years at a $1\frac{1}{2}$ to 1 slope, and will then subside in places to a much smaller slope, upheaving the bed of the canal below it. A movement of this nature occurred in the Calcutta Docks in 1890, and is described in a report* which tends to show that the angle of repose of this soil may be as small as $7\frac{1}{2}$ to 1, although it will stand under certain circumstances at $1\frac{1}{2}$ to 1, and even at a steeper slope. In the black soil, trunks of trees and layers of peaty matter are found, which probably account in some degree for the treacherous nature of the subsoil. Experiments were made by Mr. Leonard in 1873, to determine the amount of settlement which would be produced by imposing various loads on this soil at different depths from the surface; and Mr. Apjohn (in a note written in 1881, from which the following facts are largely taken), produced from these experiments the diagram on the next page. Fig. I. shows the results in the upper loamy soil, and Fig. II. those in the bluish-black clay.

The experiments on which these diagrams are based were made near Calcutta, on piers built at the different depths stated, which had a bearing surface of 10·24 square feet each. They were loaded so as to induce a pressure varying from 1·5 to 8·7 tons per square foot. Each pillar was loaded with three different weights, increasing by a ton per square foot, and the weights were left on until no further sinkage could be observed. The experiments were perhaps not sufficiently numerous to justify the formation of any general law upon the recorded facts, but, working on these experiments, Mr. Apjohn drew the conclusions

* Report by Mr. J. H. Apjohn, Engineer to the Calcutta Port Commissioners, on the recent movements of the walls of dock No. 1, dated December 1, 1890.

that the curves representing the settlements were hyperbolas, the amount of settlement increasing in a geometrical ratio as the pressure itself increased arithmetically; that the ratio of each geometrical series pertaining to the respective depths decreased with the depth, and that the rate of decrease appeared to conform to a law, viz. that as the depth



DIAGRAMS OF SETTLEMENT OF FOUNDATIONS.

of foundations subjected to pressure increases in arithmetical progression, the ratio of the geometrical series, representing the rate of sinkage, decreases in a geometrical series of which the ratio is less than unity. However this may be, it is evident that great care is necessary in founding any masonry structure on such soil as that referred to in Fig. II., in which a pressure of 1 ton on the square foot causes a settlement of 1 inch, and a pressure of 4 tons causes a settlement of 10 inches. For, unless the pressure on the foundations is fairly equal all over the area of them, there must be unequal settlement, and consequently cracks in the masonry. The results of unequal pressures are clearly shown by an investigation which Mr. Apjohn made of the strains imposed on a lock wall founded on this soil. The particular case taken was that of the Gaowkhally Lock, in Bengal, which cracked in the manner shown in Plate LXXXIII., part ii., although special care was taken in its construction. A wedge of sand, weighing 90 lbs. to the cubic foot, was introduced behind the walls, and the earth backing, which was not carried up to the full height of the wall, was thoroughly consolidated by ramming. The earth itself weighed about 112 lbs. to the cubic foot, so the sand had the effect of reducing the vertical pressure on the back footings of the foundation; but the thorough consolidation of the earth backing had the effect of reducing the pressure exerted by it against the back of the wall, which appears to have been a disadvantage, for as the crack in the floor was due to the wall falling backward, it is evident that the crack might have been avoided had the pressure against the back of the wall been greater. Indeed, it is probable that

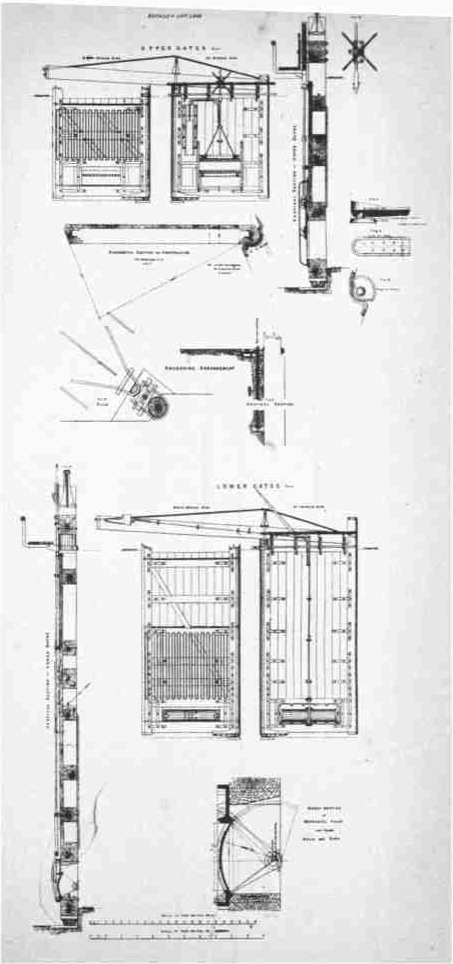
at the time the lock cracked, which was before any water was admitted to it, the earth pressure was practically confined to that due to the sand filling alone, and that the earth backing exerted no thrust. The sections Figs. I., II., and III., show the three principal parts of the lock wall; the forces acting upon them have been ascertained by the methods described in Appendix XI. P in each case is the vertical component of the thrust of the earthwork, and of the weight of a section of the wall one foot in length, that is to say, P is the weight of the wall and the wedge of backing A E D which lies vertically over the foundations. P_0 shows the point of application of P, when there is no earth thrust, P_1 when the thrust is due to an angle of repose of 1 to 1, P_2 when the angle of repose is 2 to 1, and so on. H T_2 is the horizontal thrust of the earthwork when the angle of repose is taken as 2 to 1, H T_5 when the same angle is taken as 5 to 1.

The line drawn vertically through P_0 passes through the centre of gravity of the wall and wedge A E D combined, and it cuts the base C D at a point which is the centre of pressure on the base *if the horizontal thrust is not in operation.* If the horizontal thrust is taken to be in operation, and is that due to an angle of repose of 2 to 1, the vertical component of the total pressures acting on the base is P_2, acting at the point where the resultant R_2 of the earth pressure and weight of the wall cuts the base C D. P_2 is of course equal in amount to P_0, but is transferred nearer to the centre of the lock by the action of the horizontal thrust of the earthwork. The pressures P_0 D and P_0 C represent the intensity of pressure at the points D and C respectively, caused by the force P_0 acting at its point of application: P_2 C and P_2 D being the corresponding pressures due to P_2 (these have been obtained by the method explained in Appendix XI. para. 4). Thus, taking the case of the section through the chamber wall, the total pressure on the base of the wall is 29 tons, or an average of 1·2 tons nearly per square foot, on the 26-foot base: if the earth backing exerts no horizontal thrust, then the centre of pressure is on the line P_0 and the pressure (P_0 D) at D is 1·9 tons per square foot and the pressure (P_0C) at C is 0·3 tons per square foot. It will be seen from the second diagram on page 216 that a pressure of 1·9 tons would cause a settlement of about 1½ inches, but a pressure of 0·3 tons would cause a settlement of about one-third of an inch only. If the horizontal thrust of the earthwork (calculated on a 2 to 1 slope) is brought into account, the pressure at D (P_2 D) becomes 1·5 tons per square foot, and that at C becomes 0·7 tons; the settlements due to these pressures are about 1 inch and ½ inch respectively, which would be sufficient to crack

the floor, though hardly to the extent shown; and it is very probable, as has been already stated, that at the time the floor did crack, the earth did not exert any horizontal pressure. Had the earthwork not been so carefully rammed, but left to exert the full pressure due to its natural angle of repose, the extent of the cracks would have been less; they would have been entirely prevented if the earth thrust had been sufficient to cause the resultant to pass through the centre of figure of the base of the wall. It will be seen that this would have been the case in Fig. II. if the angle of repose had been 5 to 1 and the earth backing had exerted the full pressure due to that slope: but that even with that angle of repose the resultant of Fig. III. still passes at the back of the centre of the base.

The cause, then, of the cracks which have often occurred in lock floors is, primarily, that the design of the walls has been such that the centre of pressure of the weight of the wall and superincumbent earth (E B D) fell so far behind the centre of figure of the base that the unequal pressures brought upon the surface of the base caused unequal settlements sufficient to crack the floor. And a secondary cause was the insufficient support afforded to the wall by the earth pressure. It is noticeable that in most cases these cracks have appeared before water was admitted to the lock, and often before the walls were raised to their full height: the water pressure would of course tend to increase the backward motion of the wall and to increase the evil. The section of the main walls of the older locks varied a good deal in different parts—the tail-bay, fore-bay, counterforts, and chamber—so that any tendency to crack was increased by the unequal pressures resulting from these changes, and long wing walls were built which were liable to unequal settlement.

In the more recent locks, Plate LXXXII., which have been built in the soft soil of Lower Bengal, wing walls have been omitted and the earth slopes have been retained by laterite revetments (which can settle without affecting the lock), and the section of the lock walls has been kept more uniform. Fig. IV. (part ii. of the plate), is a section of the lock wall adopted on the Coast canal: the centre of gravity of the wall alone lies immediately above the centre of figure of the base, and the centre of gravity of the wall together with the superincumbent earth (A E D) lies 2·6 feet behind the centre of the base; so that, if the earth backing exerted no horizontal thrust at all, the pressure at D (P_0 D) would be 1·9 tons and at C (P_0 C) 0·6 tons. But the backing was tipped in behind the wall and not rammed, so that it must certainly have exerted some pressure on the wall. The horizontal thrusts due


UPPER GATES
LOWER GATES

to the angles of repose of 1 to 1, 2 to 1, &c., are shown as H T_1, H T_2, &c. (see Appendix XI., para. 2), and the lines of action of the resultants are shown as R_1, R_2, R_3, &c. It will be noticed that when the angle of repose is 2 to 1, the resultant R_2 passes almost through the centre of the base; so that, if that angle was the true one, the pressure on the base would be uniform throughout. It is probable that the true angle is less than 2 to 1, and that the resultants have been thrown further in toward the centre of the locks: for these locks have not cracked. If the line of action of the resultants cuts the base on the inner side of the centre of the base, the tendency of course is for the wall to fall forward: it is better that the tendency should be in this direction, because the floor counteracts any forward motion of the wall, and the water pressure does the same. It will be noticed that even with an angle of repose of 5 to 1 the resultant cuts the base only 3·2 feet from the centre of it. In constructing works on this soft soil it is most desirable to avoid unequal pressures during the progress of the work, so that the settlement of the foundations, which must occur, may proceed regularly. One of these Coast Canal locks sunk 12 inches bodily during its construction. If different horizontal sections of the wall in Fig. IV. are taken and the earth backing is kept up to the level of the top of the section, it will be found that, with an angle of repose of 2 to 1, the pressures on the base are nearly equalised, so that as the building progressed the lock sank equally all over its foundation.

Unequal pressures are, of course, greatly reduced by increased width of base. In the Gaowkhally lock the base was 0·75 of the height: in the Orissa Coast Canal locks the base was nearly 0·90 of the height, and in the Chitpore lock the base was 1·1 of the height. In the latter case (Plate LXXXII., and Fig. V., part ii.) the back of the wall was lightened by voids, so that, with earth pressure calculated at an angle of repose of 2 to 1, the resultant of that pressure and the weight of the wall passed through the centre of figure of the effective base.

In all works built on soil liable to settlement in the manner indicated by the diagrams on page 216, and of which the angle of repose is so uncertain, the resultants of the earth pressure and weight of wall (taking any probable angles of repose—say from 1 to 1 to 5 to 1) should fall within a distance of the centre of figure of the base not greater than about one-tenth part of the width of the base.

Plates LXXXIII. and LXXXIV. show single and double locks as constructed in Bengal, and Plates LXXXV. and LXXXVI. show the timber lock gates, with balance beams, which have been erected on the

Orissa and Midnapore canals in Bengal, with the various forms of gate valves which have been employed. The semi-cylindrical valve on the Midnapore canal gives great satisfaction, and so does the parallel bar valve (Plate LXXXVII.) which was introduced by Mr. Fouracres on the Sone canals. This valve is removed from its seating by the action of the parallel bars, as soon as the spear by which it is connected to the lifting gear has been raised slightly, so that there is no friction to be overcome. It is lifted by a rack and lever by one man in about thirty seconds, and is closed by simply turning the paul out of the rack, when it falls by its own weight. The various arrangements shown in these plates are all more expensive than an ordinary draw-valve lifted by rack and gearing, and it is questionable whether they offer corresponding advantages.

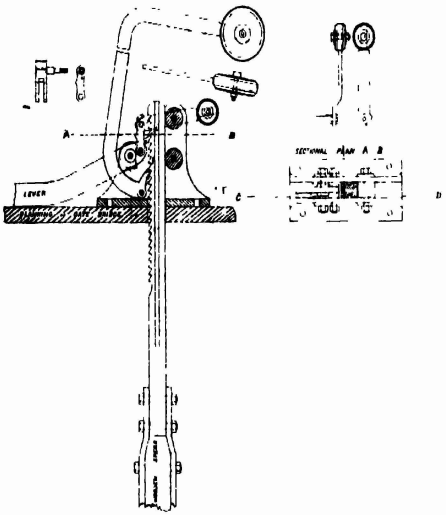
The lock gates shown on the foregoing plates are actuated by the old balance beams. These are now rarely used, and in Bengal all new lock gates are actuated by the arrangement shown on Plate LXXXVIII., which was also introduced by Mr. Fouracres. The example in the illustration was designed for the Chitpore lock which is 40 feet in the clear, but in smaller locks the rack is fixed to the top of the gate and the gearing for actuating it rests on the lock wall. In that case the pinion working in the rack is mounted in a small triangular case which is pivoted in the masonry, so that it can adjust itself to the angle assumed by the rack. The pinion is keyed to a shaft which is turned by a handle similar to that in the plate.

Plate LXXXIX. shows various forms of valves for lock tunnels. The valve which has been successfully erected on the Chitpore lock was designed by Mr. Apjohn. The important point in connection with it is the ease and speed with which it can be opened: it has the objection that it cannot be readily closed, in case of any accident, until the difference in level between the water within and without the lock is small. This kind of valve has been fitted to the locks on the Orissa Coast Canal. The valve or culvert filling gear which is used on the Midnapore Canal and in Orissa is fitted with a water balance bucket in a well over the filling culvert. The arrangement is more cumbersome and expensive than that in use on the Sone canals, but it is more easily manipulated. The iron gates of the Chitpore lock, which are illustrated in Plate XC., were designed with a watertight compartment below the water line, with the object of partially floating the gate, so as to relieve the strain on the anchor irons. These gates are rather too light in structure, and great difficulty was experienced in making the compartments watertight.

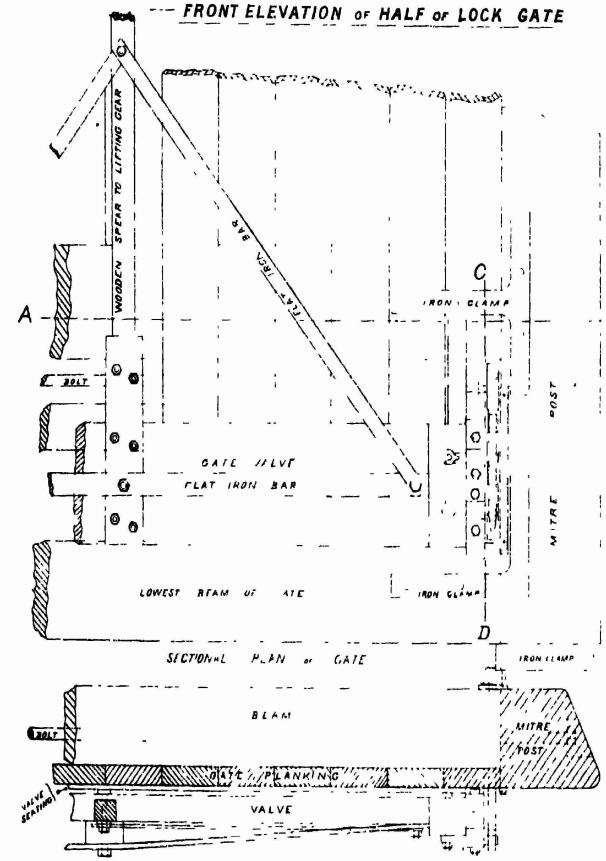
SONE CANALS
LOCK GATE VALVE AND LIFTING GEAR

SCALE
0 1 FOOT 2 FEET 3 FEET

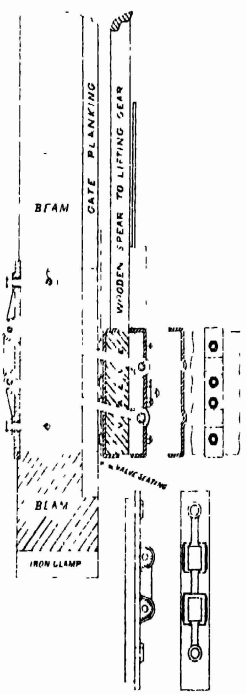
LIFTING GEAR OF GATE VALVE
SECTIONAL ELEVATION ON C.D



FRONT ELEVATION OF HALF OF LOCK GATE



SECTION C D



CHAPTER XV.

DUTY OF WATER.

Definition of the "Duty" of Water—Duties expressed in different Forms—Base of Duties—Duties in Khareef and Rabi Seasons—Duty "at the Head" and Duty "utilised"—Duties in Canals and Distributaries—Variations in Duties due to Soil, &c.—Great Variation in Duties—Low Duties display Waste—Duties during Periods of Pressure—Duties for Rice Irrigation in Bengal and Madras—Duties for Rabi Irrigation—Experiments on Duties—Duty of Water in Egypt—Gauging Canals to ascertain Duties—Duties largely affected by care in Distribution—Irrigation by Rotation or "Tatils"—Trouble and Perseverance required to establish "Tatils"—An Example of Tatil Tables.

THE "duty" of water, in the language of the irrigation official, may be defined as the area of crop which can be matured by a given quantity of water. Duties vary very greatly, and must necessarily do so. At first sight the great variations which are found in the records of duties, and the difficulties which are known to exist in recording all the essential facts accurately, leads to the opinion that "duties" are unreliable and misleading; it must be admitted that great care is necessary in dealing with them, and that serious errors have arisen from their misuse. But, since no irrigation project can be intelligently designed without calculation of the quantity of water needed for the irrigation of the crops, a study of duties is of great importance; and, if the fact is borne in mind that what it is most desirable to know is the duty of water under unfavourable circumstances when crops most need irrigation, and not the duty under favourable conditions, when, possibly, no water at all may be essential, it is more easy to seek for sound data for the necessary calculations.

The duty of water varies primarily with the crop. Rice needs more water than indigo, indigo more than wheat. It varies even more largely with the soil: sandy land—especially if the crop is rice—will take two and three times the water that clay soil will need. It varies with the season: if the rainfall is scanty, the more need for water. It varies with the condition of the channels: flat shallow channels necessa-

rily give smaller duties than steeper and deeper ones. It varies with the distance the water has to be carried in the channels, owing to the loss on the road. And it varies in no small degree with the skill with which the distribution of the water is managed, not only by the cultivators, but by the canal officers.

In India it is usual to take 1 cubic foot per second as the unit of quantity, and the whole period during which a crop requires water to bring it to maturity as the time during which the flow of 1 cubic foot per second continues. Thus, when it is said that the duty of water in the *khareef* (monsoon) season of a certain canal is 80 acres *at the head*, the statement implies that the total volume of water which passed into the head of the canal during the entire khareef season, had been ascertained, and the average discharge per second had been calculated, and that 80 acres of crop had been matured by each cubic foot of water per second which had, on the average, passed into the head of the canal. The duty, especially in the case of works where the water is stored in tanks or reservoirs, is sometimes expressed in terms of the volume of water used per acre; thus, if the duty of the water of a tank is said to have been 200,000 cubic feet per acre, it means that on the average each volume of 200,000 cubic feet *drawn from the tank* was sufficient to mature one acre. Each way of expressing the duty is easily convertible into the other, provided that the exact period of flow in the first case is known. Until recent years the duty of water in different provinces in India was in most cases simply expressed as so many acres to the cubic foot, and the period of flow, or *base* as it is now called, of the duty was rarely stated; now the base is usually given in the official returns and the total volume of water used in irrigation can be ascertained. The following simple formulæ are useful :—

D = Duty of water, i.e. the number of acres of crop matured by 1 cubic foot per second flowing continuously for a defined time.

B = Base of the duty, i.e. the number of days during which the supply of 1 cubic foot per second runs in order to mature the crop defined by the duty.

Then—

$V \frac{B}{D} \times 86{,}400$ = The volume of water in cubic feet used in maturing one acre of crop .. .. (I.)

$S = \frac{B}{D} \times 23{\cdot}8$ = Total aggregate depth, in inches, which the volume used would reach if distributed equally over the area irrigated .. . . (II.)

Further:—

If x = The discharge in cubic feet per second necessary to irrigate a given area of crops (A) with a given duty (D) and base (B);

Then—

$$x = \frac{A}{D} = \frac{A\,S}{B \times 23{\cdot}8} \quad .. \quad .. \quad .. \quad .. \quad \text{(III.)}$$

The two chief crops in India are the khareef and the rabi crops. The khareef crop is grown in the monsoon months (June to October) when there is the annual heavy rain. The rabi crop is grown during the cold season (generally November to March.) The following table shows the duty of water taken *at the head* of the canal in the khareef season for five years on some of the older canals in different provinces :—

DUTY IN KHAREEF SEASON.

Canal.	Number of Acres of Crop matured by 1 cubic foot per second.				
	1885 86.	1886–87.	1887-88.	1888 89.	1889-90.
Bengal :—Sone	80	95	74	65	68
N.-W. Provinces :—					
Upper Ganges	78	80	66	73	83
Eastern Jumna	90	92	94	104	94
Punjab :—					
Western Jumna.. ..	86	66	90	73	78
Bari Doab	59	69	61	62	58
Madras :—					
Kistna	..	145	101	106	114
Penner	..	130	193	168	147
Bombay :—Mutha	98	52	49	53	114

and the following table refers to the rabi crops, but is based on discharge "utilised" and not on that *at the head* :—

DUTY IN RABI SEASON.

Canal.	Number of Acres of Crop matured by 1 cubic foot per second.				
	1885-86.	1886-87.	1887-88.	1888-89.	1889-90.
Bengal:—Sone	99	78	68	78	52
N.-W. Provinces:—					
Upper Ganges	171	139	155	168	143
Eastern Jumna	129	130	108	124	153
Punjab:—					
Western Jumna	96	134	48	107	123
Bari Doab	153	128	125	141	169
Bombay:—					
Nira	60	69	..	106	95
Jamda	..	24	19	47	33
Krishna	22	32	31	25	36
Ekruk Tank	28	20	24	41	56

These statements do not show the "base" of the duties, and they are consequently useless to determine the total volume of water used on the crop, but they are useful as a gauge of the area which a canal of a given capacity will irrigate effectively, and as a gauge of the area which can be efficiently irrigated from a given discharge. The older canals have been selected, as the results obtained from them are in many ways more trustworthy.

But the great variation in "duty" which obtains, even on the oldest canals, is well illustrated by the following figures,* which show the duties on the Bari Doab Canal in the month of November, for a period of ten years. The duties during this month are especially important, as November is the month in which the rabi sowings are principally made, and the duty which can be obtained in that month may determine the area of the crop which can be sown :—

* Taken from Mr. Higham's Note of 28th September, 1891, on the Chenab Canal Project.

DUTIES IN NOVEMBER ON THL BARI DOAB CANAL.

Year.	Rabi Area.	Average Supply entering the Canal during November.	Duty on November's Supply.
	acres.	cubic feet per second.	acres.
1881–82	241,130	2,164	111
1882–83	207,144	2,533	81
1883–84	229,933	2,275	101
1884–85	240,574	2,557	94
1885–86	315,447	2,404	131
1886–87	241,945	2,105	114
1887–88	266,610	1,955	136
1888–89	295,188	2,171	135
1889–90	314,935	2,029	155
1890–91	314,142	2,268	138
Average of ten years	266,705	2,246	118

It will be seen that the "duty" of 1 cubic foot a second varies from 81 to 155 acres, and that the average was only 118 acres.

The duty of water may be gauged at all parts of an irrigation system, but it is usually stated with reference to an entire system on the discharge gauged in the canal below the head-sluice, and it is stated in two ways: first, on the basis of the discharge actually gauged, which is termed the discharge *at the head* of the system; and, secondly, on what is termed the discharge "utilised." The first way of stating the duty is useful, since it shows the quantity of water which it is necessary to draw from the source of supply—river, tank, or reservoir—in order to effect a certain result; but, inasmuch as the quantity of water on which the duty is based includes water wasted, run out at escapes, used in navigation, or lost in various ways, it is not a true gauge of the water used in the fields in which the crop is grown. The discharge "utilised" is obtained by deducting from the discharge "at the head" the quantities of water which are gauged as run out at escapes or used for other purposes: so the duty, based on the discharge "utilised," does become a true gauge of the quantity of water which it is necessary to draw simply for the purpose of irrigating and maturing a stated area of crop. It is not, however, an accurate measure of the quantity of water actually placed on the fields, because the deductions made from the dis-

Duty of Water in the "Khareef" or Monsoon Season of 1889–90.

Canal.	Average Discharge of the Canal at Head during the Season.	B = Base.	D = Duty of :—		S = Equivalent Aggregate Depth of Water on the Fields on the Basis of :—		V = Volume "utilised" per Acre Irrigated.	Rainfall.
			The Discharge at Head of the Canal.	The Discharge "utilised."	Discharge at Head.	Discharge "utilised."		Proportion of the Fall of the Year to the Average Fall.
	cubic feet per second.	days.	acres per cubic foot per second		inches.	inches.	cubic feet.	per cent.
Bengal :—								
Orissa	2,196	122	82·3	96·5	35	30	109,230	2 below.
Midnapore	531	122	109·5	122·0	26	24	86,400	8 above.
Sone	3,512	122	68·4	81·9	42	35	128,700	4 below.
N.-W. Provinces :—								
Upper Ganges ..	3,412	134	83	90	38	35	128,640	20 below.
Lower Ganges ..	2,389	134	58	74	55	43	156,450	11 „
Agra	1,186	108	54	74	48	36	126,090	16 „
Eastern Jumna ..	1,051	165	94	99	42	40	144,000	11 „
Punjab :—								
Swat River ..	472	170	51	52	79	78	282,470	18 „
Western Jumna ..	2,370	183	78	101	56	43	156,540	26 „
Bari Doab	3,593	182	58	65	74	66	241,920	23 „
Sirhind	2,305	170	43	50	94	81	293,760	27 „
Chenab	245	175	112	114	37	36	132,630	11 above.
Sidhnai	1,028	174	61	61	68	68	296,450	29 below.
Madras :—								
Godaveri	4,252	214	144·8	Not stated	35	..	*127,700	49 above.
Kistna	3,764	214	114·6	„	44	..	*161,340	Normal.
Penner	416	215	147·4	„	34	..	*126,020	24 above.
Sungam	638	215	92·5	„	55	..	*200,910	Normal.
Bombay :—								
Nira	165	273	59·5	75·5	109	86	312,410	11 below.
Mutha	134	273	56·9	Not stated	114	..	..	11 above.

* Based on the *discharge at head*, as the discharge "utilised" is not stated; the difference would not very largely affect the volume in this case.

Duty of Water in the "Rabi" or Cold Weather Season in 1889–90.

Canal.	Average Discharge of the Canal at Head during the Season.	B = Base.	D = Duty of :—		S = Equivalent Aggregate Depth of Water in the Fields on the Basis of :—		V = Volume "utilised" per acre Irrigated.
			The Discharge at Head of the Canal.	The Discharge "utilised."	Discharge at Head.	Discharge "utilised."	
	cubic feet per second.	days.	acres per cubic foot per second.		inches.	inches.	cubic feet.
Bengal :—Sone	1,850	119	40·4	52·1	70	54	197,340
N.-W. Provinces :—							
Ganges	3,885	182	132	143	33	30	109,950
Lower Ganges ..	3,637	182	99	128	44	34	122,850
Agra	1,207	182	95	112	46	39	140,400
Eastern Jumna ..	987	182	146	155	30	28	102,770
Betwa..	467	168	45	58	88	69	250,260
Punjab :—							
Swat River ..	534	178	126	130	34	32	118,300
Western Jumna..	2,330	182	101	123	43	35	127,840
Bari Doab	1,862	181	169	169	25	25	92,530
Sirhind	2,839	182	137	146	32	30	107,700
Chenab . ..	282	140	42	47	79	70	257,360
Bombay :—							
Nira	147	92	82·4	95·4	26	23	83,320
Hathmati	48	92	30·0	60·0	73	36	132,480
Mutha	151	92	37·6	..	58	..	..
Krishna .. .	75	92	27·0	36·0	81	61	220,800
Jamda .. .	39	92	32·4	32·4	67	67	245,330
Bhatodi Tank .	6	92	207·9	234·6	10	9	33,880
Matoba Tank ..	8	92	133·5	133·5	16	16	59,540
Revari Canal ..	8	92	124·0	153·0	18	14	51,950
Yerla River Works	21	92	53·0	65·0	41	33	122,290

charge "*at the head*" include only known and measured losses, and they do not include the losses from percolation, absorption, and evaporation, which cannot be accurately gauged. These losses are sometimes very large, especially where small areas are irrigated at a distance from the head of the canal, and they materially affect the duty which can be obtained from that portion of the supply taken in at the head which is "utilised." This explanation will enable the reader to grasp the true meaning of the statistics of duties given in the tables on the two preceding pages.

But although the duty of the water drawn in at the head of a system is a useful factor in many ways, it is often most desirable to gauge it at other points in the system, and with reference to different "bases," that is to shorter periods of time, than that of the whole irrigating period of a crop: for the duty based on the discharge drawn from the source of the supply on the average of the whole season, fails to take cognisance of fluctuating demands. It is necessary in most cases to know not only the average discharge of a season, but the maximum discharge required at a period of pressure during the season.

In the North-West Provinces statistical tables are prepared annually which show the duty of the water in the distributaries. These duties are calculated with reference to the discharge at the head of the distributaries, and so all loss by escapes, leakage, and all other causes between the river and the distributary is eliminated. The following table shows the facts of the kharcef season on the distributaries of the Ganges Canal for five years:—

DUTIES ON THE GANGES CANAL IN THE KHARIF SEASON.

	1885-86.	1886-87.	1887-88.	1888-89.	1889-90.
	acres.	acres.	acres.	acres.	acres.
Duty of the canal on its *discharge at head*	78	80	66	73	83
Duty of the canal on its *discharge* "*utilised*"	86	100	69	76	90
Duty of the distributaries on their *discharge at head* ..	88	102	72	76	95
Base of the above duties	115 days	137 days	103 days	111 days	134 days
Volume of water in cubic feet used (at the distributary head) per acre	113,260	115,690	122,400	125,450	121,970

The duties in the distributaries in all cases show, of course, better results than the duties in the canal, because the water in the distributaries is not subjected to many of the causes of loss which affect the supply in the main canal: if the duties had been gauged—as they sometimes are in individual cases—at the outlet from the distributary into the village channel, the duties obtained would have been still higher, and the volume of water actually passed on to the fields would have been less—probably 20 per cent. less—than this statement shows. The results given in the above table were obtained on a canal which has been in operation since 1855; the irrigation is well developed and the administration thoroughly organised.

The following table shows corresponding figures for the Lower Ganges Canal, which was brought into operation about 24 years later: it refers to the khareef season also:—

DUTIES ON THE LOWER GANGES CANAL IN THE KHAREEF SEASON.

	1885-86.	1886-87.	1887-88.	1888-89.	1889-90.
	acres.	acres.	acres.	acres.	acres.
Duty of the canal on its *discharge at head*	43	33	41	53	58
Duty of the canal on its *discharge "utilised"*	69	64	60	72	74
Duty of the distributaries on their *discharge at head*	95	88	102	104	94
Base of the above duties	115 days	137 days	103 days	111 days	134 days
Volume of water in cubic feet used (at the distributary head) per acre	104,510	135,040	87,120	91,480	121,970

The loss of water between the head of the canal and the head of the distributaries in this case varies from 20 to 40 per cent. These statements show the variation of duty on different groups of distributaries during the same year, but the variation between the duties of individual distributaries of the same group would be even more marked. Thus, in the case of fifteen distributaries in the Meerut division of the Ganges Canal, which had an average duty of 105 acres during one khareef season, it was found that the duties of individual distributaries varied from 80 to 126 acres. And the divergence may be much greater. For instance, the

Sakla distributary in the Sone canals in Bengal, which irrigates lands which are for the most part clay, was gauged, one khareef season, as working to a duty of 115 acres to the cubic foot, while the Kaithee distributary, close by, but which ran in sandy soil, attained at the same time to a duty of 67 acres only.

The statistics given by the canal reports render it possible to carry a little further the analysis of the duty of water on the Ganges Canal. The table given above shows the duties on the distributaries taken collectively; the following table shows the duties in 1889-90 on the same distributaries during the khareef season, taking them in five groups according to the administrative divisions :—

DUTIES ON DISTRIBUTARIES OF GANGES CANAL IN KHAREEF SEASON.

Distributaries	Duty of each group of Distributaries on its discharge at head. Base 134 days.	Volume of water in cubic feet used per acre.
	acres.	
Distributaries in the Northern Division	70	165,530
" " Anupshahr "	102	113,260
" " Meerut "	91	126,320
" " Bulandshahr "	102	113,260
" " Alighar "	95	121,970
All the distributaries taken collectively	95	121,970

The tables which have been given in this chapter show the great variation which occurs in duties in different canals and in different parts of the same canal system. They show that the duty of a cubic foot of water "utilised," in the khareef season, may vary from 50 to 150 acres, and in the rabi season from 30 to 230 acres, and that, when the "base" of these duties is taken into account, the volume of the discharge "utilised" which is necessary to mature a "khareef" crop appears to vary from below 100,000 to above 300,000 cubic feet, and in the "rabi" crop from about 35,000 to as much as 250,000 cubic feet. It may be thought that such widely divergent results can be of little value. Such divergence is, however, to be expected from the nature of the case, and the results obtained are chiefly valuable as a record of what may be expected in cases where the circumstances are similar, and as a warning against

too sanguine anticipations. But duties are not only valuable in judging of the probable results in any project which is under review, but also in comparing the efficiency of the canal management in a running canal, on which the duties are worked out, for a series of years, on one regular plan. It must be admitted, however, that an intimate acquaintance with the circumstances is essential to enable an observer to draw a sound conclusion. For instance, it will be seen from the tables that on the Jamda Canal in Bombay, where nearly half the total area under irrigation in the "rabi" season is wheat, the duty of the season was 32·4 acres per cubic foot per second to a base of 92 days on the "utilised" discharge. This is equivalent to 245,330 cubic feet in volume per acre irrigated. This was the volume, it must be remembered, which was taken from the source of supply after making deductions for actual gauged losses. But experiments were conducted on this canal by gauging the discharge actually run on to the fields of wheat in two cases, and it was found that the duty of the water *at the field*, to the same base of 92 days, was 86 acres in one case and 126 acres in the other, corresponding to volumes of 91,704 and 62,725 cubic feet per acre, which are reasonable quantities of water (25 inches and 17 inches respectively) for a wheat crop. The right conclusion to be drawn from the extremely low duty of the canal generally was, that very large quantities of water were lost or wasted between the head-sluice and the fields. This is a result which is not uncommon in Bombay, where the water is often led for considerable distances from the source of supply, along shallow channels to irrigate fields scattered widely over the district, and this is the chief explanation of the very low duties which are obtained in that province. In the Hathmati Canal, for instance, it is stated that 50 per cent. of the supply is lost by absorption and evaporation in the first 10 miles. Irrigation under such conditions must be wasteful of water.

In all cases it is very important to ascertain the duty of water in periods of pressure; especially where, as in Bengal and Madras, the area under irrigation during a season is almost entirely one kind of crop. In those provinces the "khareef" crop is practically all rice. In the North-West Provinces and the Punjab it consists of indigo, cotton, and rice. Where there are several different kinds of crops grown in the same season the available supply of water can be more equally distributed, and there is not the same intensity of demand at the same moment. With reference to this point the actual necessities of the crops do not only rule the demand, but, not unfrequently, the customs and prejudices of the people have to be reckoned with. This is exemplified in the case of the Sone

canals in Bengal. The khareef crop is almost entirely rice. The people had been accustomed for centuries, before the canals were made, to mature the crop entirely from the local rainfall; in good years the crop did well, in bad years it almost entirely failed. To a certain but small extent the crop was irrigated from small tanks in which the local rainfall was impounded. The rainfall of the monsoon is divided by the people into *nechutras* or periods which are regularly fixed by the phases of the moon. They have become accustomed to consider water necessary during the particular periods at which they reckoned that the rain generally fell, and above all things they considered it essential that the rice should be copiously supplied with water during the ten or twelve days of the "Hathia" *nechutra* in October. To a considerable extent no doubt the supply of a copious volume of water at this time is really essential to the crop from a purely agricultural point of view, but it is probably not essential that this copious supply should be all delivered on the fields within one particular period of about ten or twelve days. But here the custom or prejudice of the people is a force. They drain off their fields to a considerable extent before the "Hathia" in anticipation of a heavy rainfall, and if the "Hathia" rain fails, the demand becomes most intense and a strain is placed, for rather less than a fortnight, on the canals, that taxes every point of the system. So much is this the case that the irrigation officers limit the area which they will undertake to irrigate, not by the duty of the water based on the results of the working of the entire season, but on the duty of the water based on the area which can be watered in about twelve days. The duties which have actually been obtained on the discharge at head of these canals during these periods of extreme pressure have varied from 42 to 45 acres per cubic foot per second, and it may be said that, until the people can be educated to extend the period during which they require so copious a supply in so short a time, the area of rice which can be irrigated by these canals must be restricted to that due to a duty of about 45 acres on the maximum discharge. It will be seen from the table on page 223 that the duties, calculated to the base of the whole season, have varied from 65 to 95 acres; in this case, these duties, though accurate in themselves, are insufficient to gauge the area which it is possible to irrigate from a channel of a given capacity. A duty of 42 acres to a base of ten days is equivalent to a depth of 5·6 inches on the fields if the entire supply "utilised" reached them, and it is certain that in the Sone canals, during a period of pressure, a very large proportion—probably at least 70 per cent.—does reach the fields. This has been

checked, to some extent, by experiments recorded on the fields themselves; it was found that a discharge of 1·26 cubic feet a second, running for 10 days 8 hours and 47 minutes, fully irrigated—according to the views of the cultivators—an area of 80 acres. This is equivalent to a depth of almost exactly 4 inches in the fields. This, in itself, is a reasonable amount of water to be required during ten days, but the difficulty is due to the fact that it is during the same ten days of the "Hathia" that this demand occurs. Every cultivator wants the water at the same time. In Madras, where the irrigation is also almost entirely confined to rice, it is the general rule that the duty of water in large channels may be taken as 66 acres to the cubic foot for any base: this duty is about 50 per cent. greater than that which can at present be realised on the Sone canals if the needs and the customs of the people are satisfied.

In the case of storage works in Madras, irrigating rice lands in their immediate vicinity, it is considered necessary to allow 200,000 cubic feet of water to each acre irrigated for the entire season: this is equivalent to a duty of 80 acres to the cubic foot to a base of 185 days.

In the case of irrigation in the rabi season, the demand for water is subject, of course, to great variations; but, as the crops are more varied and at different stages of maturity, a simultaneous demand for water for all the crops is rare, and is spread over a longer period than in the case just mentioned. It will be seen, from the statements given above, that the variations in rabi duty are even greater and more perplexing than those for the khareef season, even when the different "bases" are allowed full weight. To a very large extent these great differences are to be read as warnings of the impossibility of effecting economical irrigation over widely scattered patches of irrigation. The low duties are mainly due to large losses between the head of supply and the fields.* Thus the duty for the rabi crop on the Nira Canal in Bombay, where the channels are long and irrigation is scattered, is given as 95·4 acres, but the duty which was realised in five distributaries of the canal, reduced to the same base of 92 days, was 123 acres, which is equivalent to a volume of 64,170 cubic feet per acre, as compared with 83,320 admitted at the head of the canal, or a loss of nearly one-fourth of the supply. On an irrigation system, which actually irrigates a large proportion of the area under command, duties of 120 to 180 acres to a base of 150 days (equivalent to 108,000 and 72,000 cubic feet per acre) on the discharge "utilised" can be obtained without difficulty. And, in selected distributaries, duties of 200 to 250 acres (64,800 and 51,840

* See Chapter IV., on Absorption.

cubic feet per acre) are not uncommon to bases of 100 days or more. But it is probable that, in periods of pressure, higher duties than 100 acres to a base of 15 days cannot be expected on the discharge "utilised" in an extended system of canals. This is equivalent to the statement that the whole area of a rabi crop under irrigation may, in times of great pressure, demand a "utilised" discharge at the head of the system of 12,960 cubic feet in 15 days per acre, which (if the whole supply reached the field) is equivalent to 3·57 inches in depth. This, in ordinary cases, where the loss from absorption, evaporation, and other causes was moderate, might result in an actual depth of water delivered in the field of 2 to 2½ inches. The depth given by irrigation from wells rarely exceeds that amount.

VOLUMES OF WATER CONSUMED AT THE FIELD IN BOMBAY.

	Volumes in cubic feet used in maturing the Crops named.				
	Rice.	Wheat.	Sweet Potatoes.	Ground-nut.	Sugar-cane.
Mhasvad Tank	..	57,400	49,257 88,251	86,121	
Lower Panjhrah Works	..	90,830			
Ekruk Tank	192,550	106,790 45,364 42,800 54,740	..	82,170	479,000
Jamda Canal	..	33,463 91,704 62,725			
Krishna Canal	..	..	240,000	..	337,000
Nira Canal	..	55,641 136,162 70,501 106,060			

In the Bombay Presidency careful experiments have been made in late years to determine the quantity of water actually used in the fields for different crops. The experiments do not state the nature of the

soil in which the various crops were grown: but the variation in quantity of water used was due, no doubt, partly to the different soils. Rectangular gauge boards were erected in the channel close to the fields under irrigation; so that the quantities of water indicated are those which actually passed on to the fields. The statement on the previous page gives the results.

The average of the observations on wheat gives 73,400 cubic feet per acre, or 20 inches in aggregate depth on the field. This is certainly more than would actually be used in some soils, where three or four waterings of $2\frac{1}{2}$ inches on the field are sufficient. In the case of a reservoir project in Baluchistan it was assumed that 55,000 cubic feet of water was sufficient for a wheat crop: but this figure is a low one. Mr. Allan Wilson * gave the quantity of water required to mature a crop as 94,500 cubic feet for rice, 35,100 cubic feet for wheat and other grains, and 216,000 for sugar-cane, but these figures also seem to be too low.

The duty of water in Egypt is usually stated in terms of the number of cubic metres of water required in 24 hours for each *feddan* (a *feddan* is practically the same as an acre), but in the case of basins † the quantity of water needed is that which will give an effective depth of about one metre over the area in the time available, which is about forty days: this, after making some allowance for loss, is equivalent to a discharge of from 100 to 125 cubic metres a day per acre (4047 square metres) which may be expressed in the ordinary Indian notation as a duty of about 25 to 20 acres per cubic foot a second to a base of forty days. The lands in the basins grow *Shitwi* or cold weather crops, in December, January, and February, on the moisture accumulated in the ground during the inundation. In those cases where Shitwi crops, which consist of beans, wheat, barley, lentils, and pulses, are grown on lands which are not basin-lands and are directly irrigated during the season, the quantity of water required, during the period of the maximum rate of supply, varies from 10 to 20 cubic metres per acre per day, which, in the Indian way, would be expressed as a duty varying from 250 to 125 acres to the cubic foot, and corresponds with the rabi duty. The *Nili* crop of Egypt, which is grown in August, September, October, and November, consists chiefly of Indian corn, and the duty, during the period of maximum supply, is taken at 25 cubic metres in 24 hours per acre, which is equivalent to a duty of 100 acres to the

* 'Proceedings of the Institution of Civil Engineers,' No. 1193, April 1868.

† See page 24.

cubic foot. The *sefi*, or hot weather crops, which are irrigated in April, May, June, and July, consist of cotton, rice, vegetables, summer maize, and sugar-cane. The quantity of water required is taken as 60 cubic metres per day per acre for rice, and 30 cubic metres for the others, during the period of maximum demand. These quantities are equivalent to duties of 41 and 83 acres respectively per cubic foot per second.

For the proper determination of duties it is important to organize a regular system of gauging canals, branch canals, and distributaries at stated intervals, and to keep daily records of the discharges of all distributaries. Main canals are generally gauged daily by velocity-rods or floats: smaller canals and distributaries are occasionally gauged in the same way in order to check the daily discharges, which are recorded either from the calculated discharge of the head-sluice or by the discharge known to be due to a given depth in the first reach. The instructions for gauging canal discharges, which are in use in the Punjab, with an example worked out for a first class observation, are printed in Appendix VI.

The area of crops which can be efficiently irrigated by a given quantity of water is increased by skill in the distribution of the available supply: this skill is required no less in the actual cultivator of the field than in the engineer who controls the discharge of the various channels which are under his care. There are only a few crops which require water more than three or four (possibly five) times during their growth. Say that four waterings are required in a season of twenty weeks: it is obvious that the quantity of water required at any one moment will be reduced to a minimum if the irrigation proceeds with daily uniformity: that is, if the whole crop is irrigated once in five weeks and $\frac{1}{5}$ of the crop is irrigated in one week and $\frac{1}{35}$ of it every day. Further, since the loss from evaporation, absorption, &c., is more or less in proportion to the length of channel in flow, and is increased when the channels are running in low supply, it is economical to carry out the irrigation by a system of rotation under which the minimum length of channel is in flow at one time: and, since it is considered that there is more loss in village channels and field channels than in other parts of a system, it is an economy of water to restrict to the utmost the time during which any particular village channel is in flow. The most wasteful system of irrigation possible is that under which all branch canals, distributaries, and village channels are in use

continuously and the available supply is slowly dribbling into the fields. For, not only is the actual loss of water greater, but under this system there is also this further disadvantage that the velocities in all the distributaries and minor channels are reduced and the silt in the water, which at these points of the system is nearly always advantageous to the fields, is largely deposited in the channels, and not carried on to the cultivated ground. The system of irrigation by rotation, or by *tatils* as it is called in Upper India, is of great advantage, not only in checking the loss of water in the channels, but in teaching economical irrigation to the cultivators, and in ensuring an equitable division of the supply among the people. The most simple arrangement of tatils is that in which all distributaries and the larger channels which supply them are kept in continuous flow, and the outlets supplying the village channels are "tatiled," that is, closed by rotation, in convenient groups for a certain number of days at a time. In other cases the distributaries taking off a branch canal are similarly treated ; one group being closed for a time entirely, while other groups take the entire discharge of the canal, these being in their turn closed for a fixed period. In some cases tatils are enforced both on groups of distributaries, and then again on groups of outlets on those distributaries : but this needs not only great skill in arrangement, but great experience and practice on the part of all concerned, to make it a success. It is not often that tatils are extended to branch canals, except, perhaps, to the extent that the supply of one branch may be restricted, and that of another increased correspondingly, at stated times : if this is done, the tatil on the distributaries and outlets on each of the branches has to be adjusted accordingly. Tatils increase the efficiency of irrigation by enabling the engineers to distribute the supply available over a larger area : if they were not enforced, the cultivators near the heads of channels in flow might absorb all the supply. Where there is an abundant supply, in channels of sufficient capacity, tatils are unnecessary. As the available supply becomes—say in a year of deficient flow in the river from which the canal is drawn—more and more restricted, there is greater necessity for the strict administration of tatils ; and not only so, but it sometimes becomes necessary to alter the arrangement of the closures with reference to the quantity of water available ; for, as the supply diminishes, it is not possible to keep the same number of channels in efficient flow, consequently the number has to be reduced and the tatils or closures increased in time. It thus occurs that, in some canals where tatils have

been worked for a series of years, and experience has been gained and discipline established among the cultivators, there are regular tables showing the different arrangements of the closures for certain specified discharges of canals.

In the simplest cases, where only the outlets from the distributaries are tatiled, it is usual to divide the distributary into three lengths, so that the village channels taking off each length command areas which are approximately equal. The outlets in the first length of distributary usually get water for three days in each week, and are closed, or tatiled, for four days: the outlets in the second length of distributary are open on the four days when those in the first length are closed, and closed on the three days when the others are open: in the third length of the distributary the outlets to the village channels are allowed to be open all the week as a rule, and they absorb all the water passed on by the upper lengths. Tables are prepared showing the particular days of the week when certain outlets are allowed to be opened. Simple as this system is, it may take years of patient perseverance to thoroughly establish it.

When more complicated tatils are arranged, and closures are enforced on whole distributaries as well as on the outlets taken off certain lengths of them, it is necessary to consider longer periods of time than a week. Fortnightly or even monthly periods have to be worked out. The following tables were in use in a case where a discharge of about 360 cubic feet a second (but which varied from 345 to 380 in fact) was allotted for distribution among a group of five distributaries named V, W, X, Y, and Z, taking off a branch canal. The discharge is first divided among the distributaries according to the areas which have to be irrigated in each, so as to ensure as far as possible a regular draught of 360 feet on the canal. The table on the next page shows the days of closure of each distributary: the head-sluice is entirely closed on those days when the square in front of it contains a +, and open when it is blank.

Distributary X is open all through the month; distributary V is closed every alternate week from Tuesday to Friday inclusive, and the other distributaries as they are marked.

The diagram on p. 242 shows the working of the tatil on the first four days, distributary Y being closed entirely throughout. The dotted lines show the village channels which are in flow, the thin continuous lines show the village channels which are closed (these channels are only shown

"TATIL" TABLE NO I.

Days of the Week.	Distributary V.	Distributary W.	Distributary X.	Distributary Y.	Distributary Z.	Draught on the Canal each day.
Full supplies carried =	95	105	85	70	95	cubic feet.
F.				+		380
Sat.				+		380
S.				+		380
M.				+		380
T.	+					355
W.	+					355
Th.	+					355
F.	+					355
Sat.					+	355
S.					+	355
M.		+				345
T.		+				345
W.		+				345
Th.		+				345
F.				+		380
Sat.				+		380
S.				+		380
M.				+		380
T.	+					355
W.	+					355
Th.	+					355
F.	+					355
Sat.					+	355
S.					+	355
M.		+				345
T.		+				345
W.		+				345
Th.		+				345

from one of the five distributaries, in order to avoid confusion). The thick black portions of the distributaries are those portions which may be in flow themselves, but from which all outlets to village channels are closed. Thus distributary W is in flow and so are the three branch distributaries taking off from it, although the first sections of all are black, showing that, on the four days to which the diagram applies, the village channels from those sections are closed at their heads.

When the tatils of the distributaries have been arranged in Table I., Table II. has to be worked out for each section. The sections are mapped out in convenient groups of outlets, and the days when each section can take water are arranged, the crossed squares showing the days when the outlets are closed. For instance, on distributary V it will be seen from Table II. that the outlets on sections *v* 1, *v* 3, *c* 2, *c* 4, *a* 2, *b* 1, *b* 2, are open, and the others closed for the first four days (Friday to Monday inclusive): while on distributary W the outlets on the sections *w* 1, *d* 1, *e* 1, and *f* 1, are closed and the others open, distributary Y being

"TATIL" TABLE No. II.

	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.
DISTRIBUTARY V					+	+	+	+																				
Section *v* 1																												
" *v* 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
" *v* 3					+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Branch Distributary C					+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Section *c* 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
" *c* 2								+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
" *c* 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
" *c* 4																												
Branch Distributary A																												
Section *a* 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
" *a* 2																												
Branch Distributary B																												
Section *b* 1																												
" *b* 2																												

"TATIL" TABLE No. II.—*continued.*

	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.	Friday.	Saturday.	Sunday.	Monday.	Tuesday.	Wednesday.	Thursday.
DISTRIBUTARY W											+	+	+	+											+	+	+	+
Section *w* 1	+	+	+	+	+						+	+	+	+	+	+	+	+	+						+	+	+	+
,, *w* 2						+	+	+	+	+	+	+	+	+						+	+	+	+	+	+	+	+	+
Branch Distributary D											+	+	+	+											+	+	+	+
Section *d* 1	+	+	+	+	+						+	+	+	+	+	+	+	+	+						+	+	+	+
,, *d* 2						+	+	+	+	+	+	+	+	+						+	+	+	+	+	+	+	+	+
Branch Distributary E											+	+	+	+											+	+	+	+
Section *e* 1	+	+	+	+	+						+	+	+	+	+	+	+	+	+						+	+	+	+
,, *e* 2						+	+	+	+	+	+	+	+	+						+	+	+	+	+	+	+	+	+
,, *e* 3											+	+	+	+											+	+	+	+
Branch Distributary F											+	+	+	+											+	+	+	+
Section *f* 1	+	+	+	+	+						+	+	+	+	+	+	+	+	+						+	+	+	+
,, *f* 2						+	+	+	+	+	+	+	+	+						+	+	+	+	+	+	+	+	+

closed altogether. Then, for the next four days (Tuesday to Friday inclusive), distributary V is closed altogether and another arrangement

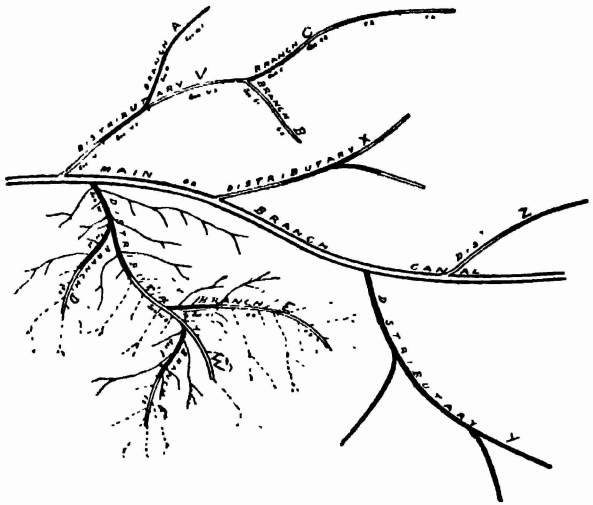


DIAGRAM ILLUSTRATING TATILS.

comes into force, Y being opened and its various sections tatiled. Table II. on the preceding page is only worked out for two of the five distributaries shown in Tatil Table No. I., page 239, and in the diagram on this page, but it is sufficient to show the system which is employed.

CHAPTER XVI.

THE ALIGNMENT OF CANALS AND DISTRIBUTARIES. DESIGN OF CHANNELS.

Alignment of Canals on the Watershed—Contoured plan of the Irrigable area—Velocity to be allowed in Canals—Dimensions of Canals—Restriction of Irrigated area—Best forms of Channel—Canals in side-long Ground—Retaining Walls in Kurnool Canal Banks—Cost of Main and Branch Canals—Design of Distributaries—Discharging Capacity of Distributaries—Silt Berms in Distributary Channels—Rules for the Preparation of Distributary Designs—Difficulties connected with Minor Channels for Rice-fields—Cost of Distributaries per mile and per acre irrigable—Outlets from Distributaries—Regulation of the Size of Outlets—Drainage of Irrigated tracts—Cost of Drainage Works.

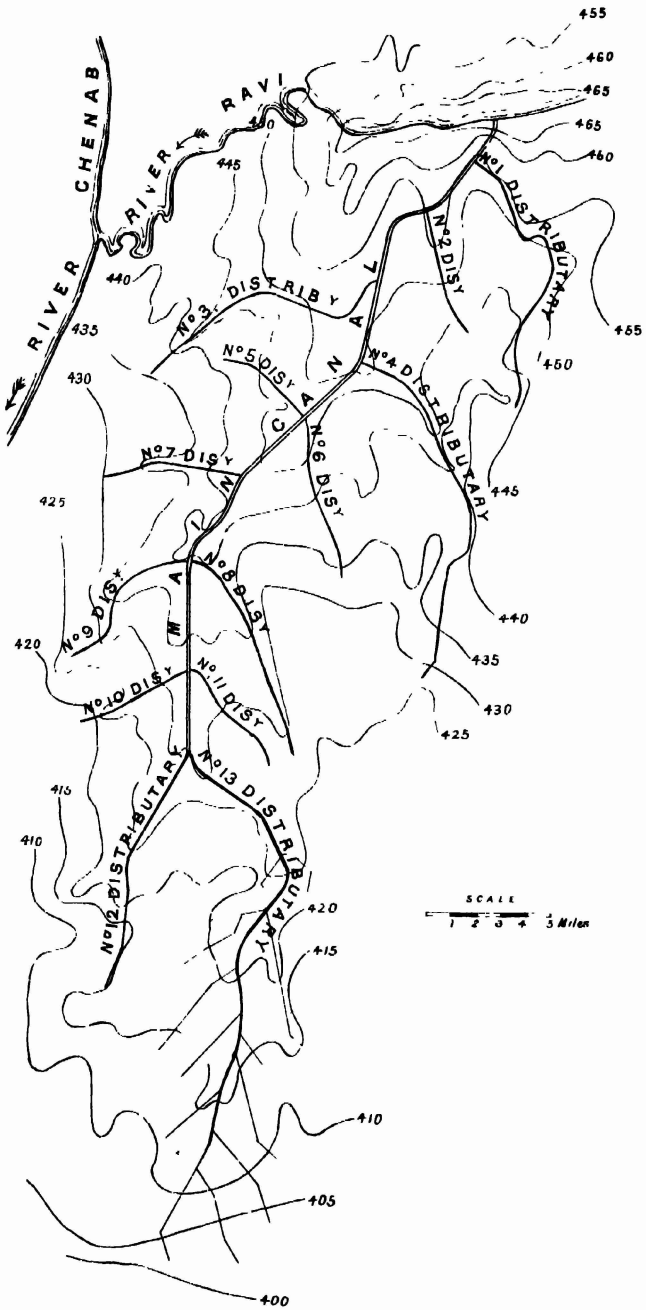
THE point of first importance in the alignment of the channels of an irrigation system is that all of them should, as far as may be possible, run on the watershed. In that position they both avoid interference with drainage and hold command over the country: an ideal irrigation system would have no cross-drainage works. But it rarely occurs that the physical features of a tract over which irrigation can be extended conform themselves so exactly to the requirements of the engineer, and, in almost all cases, the alignment of a main canal has to be determined by a balance of many considerations. One of the most weighty of these, of course, is the best position for the head-works: if there are several possible sites for these, the alignment of the canal in its upper reaches is primarily determined by the cost of the head-works and of the different routes which are possible. The highest site for the head-works may involve less depth of cutting in the canal, but a longer channel: or it may necessitate crossing heavy torrents or drainages which can be avoided by a lower head: or, it may require that the canal should be carried through an unculturable country for a long distance before the fertile land is reached. The first reach of any canal drawn from a river is always unprofitable in itself, as it is necessarily in cutting, and little or no irrigation from it is possible. The problem to be solved in connection with it is the cheapest route by which it can be constructed, so as to deliver the water on the surface of the ground at a point where

the canal can be carried along a main watershed of the tract to be irrigated. There are, of course, cases, such as that of a canal leading from a reservoir in hilly ground, or of one on the upper margin of a deltaic tract, in which the alignment of the canal must necessarily follow a contour—or very nearly follow it—along the foot of the hilly ground. In such a case the alignment may be said to be marked out by nature: but in most other cases there is room for much skill and judgment in selecting the line for the first few miles of any system.

A contoured plan of the country to be irrigated is of great assistance in determining the alignment both of main canals and of branches, distributaries, &c. Parallel lines of levels half a mile apart, or perhaps one mile apart in large projects, are run over the whole country to be dealt with, and the contours at any convenient vertical distance apart—usually five feet—are marked on it as shown in Plate XCI.

In this case the ridges and drainages of the country are shown clearly by the contours: the advancing loops indicating the ridges, the retiring loops the drainages. It will be noticed that there is a ridge which commences on the bank of the river Ravi some six miles below the head of the canal, and is well marked by the contours throughout: the canal does not follow this in the first few miles, but is carried on to it at about the point where it cuts contour 450: the alignment of the first reach is of course in less cutting than it would have been had the canal followed strictly on the ridge, and, as the head is higher up the river, a better command is obtained; but some drainage must apparently be obstructed by the first reach and is probably dealt with by drainage cuts. The distributaries should be aligned, with at least as much care as the larger channels, on the ridges whenever it is possible to do this; and, where circumstances do not permit of it, the alignment should be at right angles to the contours, that is, parallel to the general slope of the tract to be irrigated by the distributary. In the example given in the plate, Nos. 7, 8, 9, 12, and 13 run on well-marked ridges; Nos. 1 and 4 cross depressions in their course; and the others are more or less at right angles to the contours. The same principles are observed in aligning the minor channels, or village channels as they are often called, which draw their supply from outlets in the distributaries. These channels are shown in the case of No. 13 distributary in the example given. Before laying out a system of distributaries it is an immense advantage to survey the drainages independently, and to mark them out on the contoured map: this prevents any confusion arising with reference to the true watersheds.

CONTOUR PLAN SIDNAI CANAL



The main points to be considered in designing the various channels are (1) the velocity of flow which can be allowed, and (2) the quantity of water which has to be passed down them. With reference to the first point, consideration has to be given to the question of silt deposit, of the scour of the banks, and, if the canal is to be navigable, of the impediment to traffic. It is usually considered in India that a higher velocity than 2 feet a second, $1\frac{1}{3}$ miles an hour, is undesirable in a navigable canal, and a velocity of $2\frac{1}{2}$ feet a second is a marked impediment to boats towed by men or animals. If the canal is not to be navigable, the most economical velocity, as regards the size of the channels, is, of course, the highest one which the soil will stand. On the other hand, a low velocity, with, consequently, a low surface slope, will shorten the length of the upper reach of the canal, and bring the water more quickly on to the surface of the ground. But low surface slopes and low velocities mean larger channels, and, if the river carries silt, larger silt deposits in the canal head. Here all the matters concerning silt which have been discussed in Chapter III. require consideration. As a general rule the highest velocity which the soil can stand without erosion will be found the most suitable: with the proviso that it is advantageous, in almost all cases, to increase rather than to diminish the velocity of the water as it advances from the larger to the smaller channels of the system, for this tends to carry forward to the fields the matters in suspension, which are almost always beneficial. The maximum velocities allowable are:—

In light sandy soil	1·5 to 2·0 feet per second.
In sandy loam	2·5 „ „
In ordinarily firm loam	3·0 „ „
In stiff clay or *kunkur* soil	4·0 „ „
In shingle and boulders	5·0 to 6·0 „ „

There are very few main canals in India which run with a higher maximum velocity than 3·0 feet a second: a general maximum is from 2·0 to 2·5 feet.

The dimensions of a main canal are primarily determined by the "duty" of water during a period of pressure, that is, as has been explained in the previous chapter, by the quantity of water which it is necessary to pass on to the land in a short period of maximum demand. Mistakes have not infrequently occurred by working on "duties" based on the whole irrigating season instead of on this period. It has already been shown how greatly "duties" vary, and any particular case must be treated accordingly. As a general rule, main canals irrigating

khareef (or monsoon) crops should be capable of carrying a maximum discharge of 1 cubic foot per second for every 50 acres of that crop which it is intended to irrigate, and they should be capable of carrying 1 cubic foot for each 100 acres of *rabi* (cold weather) crops. The extent of land which can be irrigated may be determined either by the quantity of water available in the source of supply, or, when that quantity is abundant, by the area which can be commanded by the system. In some cases it is held to be desirable to irrigate only a portion of the area which is commanded, while, in others, no restriction is imposed. Thus, in the Madras works, and in Orissa, water is thrown widely over the largest area possible, but in the N.-W. Provinces it is generally considered desirable to restrict the area irrigated to a certain proportion (varying from 40 to 80 per cent.) of the culturable area, and in the Punjab a smaller proportion is sometimes taken. On the Sirhind Canal, for instance, only one-fourth or even one-fifth of the culturable areas are allowed to receive water. This restriction is partly due to the desire to spread the available supply of water to as many parts of the district as possible for the benefit of the people, and partly because the light soil of Upper India is liable to become water-logged, and the spring level unduly raised, if irrigation is spread over all the area commanded. This evil is not feared in less permeable soils; in Egypt, for example, the whole face of the culturable land may be said to be covered with water during a portion of the year.

The dimensions of a main canal—indeed of all channels—are usually determined by the necessities of the kharcef or monsoon irrigation, for it is during that crop that the largest quantities of water are, in most cases, required. It is rarely wise, in those cases where the average supply available is greatly in excess of the minimum supply, to base the capacity of a canal on the former quantity, but rather to provide a discharging power only moderately in excess of the minimum. For, although the minimum may occur only at comparatively long intervals, it is at the time, usually, when that minimum does occur that it is most desirable to be able to fully irrigate the area on which cultivation from the canal is practised. If the discharge of the canal, and, consequently, the area dependent on irrigation, is based on the average available supply, it is inevitable that, in a bad year, the canal must fail to fulfil the anticipations of cultivators who have sown crops to the extent which the average supply may justify.

When due consideration has been given to these points, and both the maximum discharge and limiting velocity of the main canal are fixed,

the proper form and dimensions of the canal can be determined by trial. Kutter's Formula * (Appendix III.) is generally used (with N = 0·025).† Trapezoidal sections are always used unless the canal is in rock. The trapezoidal channel which gives the maximum discharge for any given area of waterway, is that of a semi-hexagon (A, B, C, D in the diagram page 248) in which—

The hydraulic mean depth = half depth of water.

Depth of water = 0·76 $\sqrt{}$ area of waterway (nearly).

Base of the channel = 0·87 $\sqrt{}$ area of waterway (nearly).

Width at water surface = { twice the width of base or twice the length of one side slope.

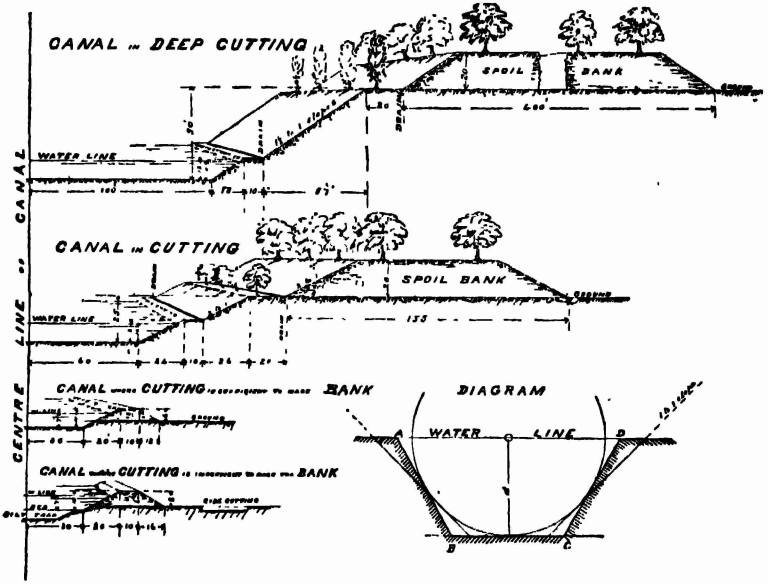
But in such a channel the side slopes are only rather more than ½ to 1 (0·58 to 1·0), and it is seldom that so steep a slope can be given in earth cutting. Neville gives the following rule for determining the best form of channel for any given side slope :—

"Describe any circle on the drawing board : draw the diameter and produce it on both sides ; draw a tangent to the lower circumference parallel to this diameter, and then draw the side slopes at the given inclinations, touching the circumference on each side and terminating in the parallel lines. The trapezoid thus formed will be the best form of channel, and the width at the surface will be equal to the sum of the two side slopes." This rule is suitable for small channels in which it is possible to make the depth great in proportion to area of the waterway, but it cannot be employed in the case of large canals unless they are drawn from rivers of great depth. For instance, the theoretically perfect channel to carry 2250 cubic feet of water at a velocity of 2½ feet a second would have :—Waterway 900 square feet ; base (0·87 × 30) 26·1 feet ; depth of water (0·76 × 30) 22·8 feet ; side slopes about 0·6 to 1. Such a channel might be suitable for an inundation canal taken from a river—such as the Nile—with a large range of level ; but it would be quite unsuitable where the depth of water in the canal is to a great extent determined by the height of the weir crest above the river bed, and by the practical difficulties and expense of excavation in deep cutting. It frequently occurs that the expense of cutting becomes very great when it has to be carried below

* Jackson's 'Canal and Culvert Tables' should lie on every irrigation officer's table.

† The coefficient was taken as N = 0·0225 in the Chenab Canal project.

spring level. The following sections are typical ones of Indian canals:—



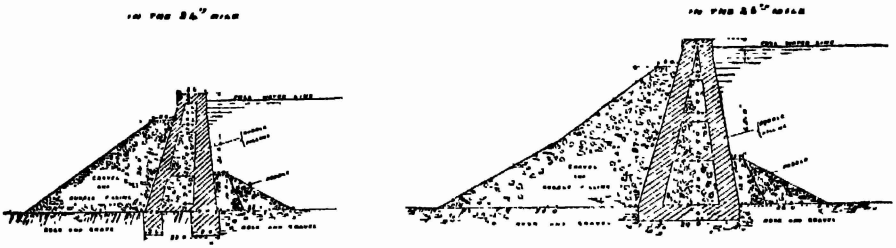
TYPICAL SECTIONS OF INDIAN CANALS.

The particular form of cross-section suitable to any particular case can only be determined by a system of trial and error, but the calculations are greatly facilitated by the use of Jackson's 'Canal and Culvert Tables.'

Where a canal is in deep cutting, as in the two upper sections, and especially in light soils, it is necessary to make a system of drains on the inner berms, or else the slopes will gutter badly: the drains on the ground level can be either led out through the spoil bank on to the fields or led into the canal. In the latter case it is necessary to make paved masonry ducts leading down the slopes into the canal. In the lowest section the case is shown where a canal is in embankment, and the cutting is insufficient to form the bank above ground-level. In such cases it is sometimes made up by cutting silt traps below the canal bed, as shown in the sketch. This is a good plan where there is much silt, but, if that is not the case, it is not a good plan, as there would be considerably increased loss of water by absorption, especially in porous soils. Under those circumstances side borrow pits are better.

When a canal is carried on side-long ground, one bank is sufficient to form the canal; many of the canals leading from the larger Bombay tanks are made in this way. Where the slope of the ground is steep,

this method is suitable, and, indeed, unavoidable; but where the slope is gentle, the width of the canal at the water-line is necessarily great, and there is much loss of water from absorption and evaporation. Considerable lengths of the Kurnool Canal in the Madras Presidency are made with only one bank, and in parts the side bank is as much as 50 feet in height: there are some miles of banks more than 35 feet in height. In most cases the banks are made of earth only; in others of dry rubble walls with a puddle core between them, faced on the water side with a gravel slope covered with puddle and rubble pitching; in other cases masonry walls, varying from 12 feet to 45 feet in height, were constructed. The following sketch shows two examples of masonry walls in lieu of banks as actually constructed on the Kurnool Canal in Madras.



MASONRY SIDE WALLS OF THE KURNOOL CANAL, MADRAS.

The statement on the next page shows the cost per mile of some of the chief perennial canals in the upper provinces of India; the corresponding figures for the Madras Canals cannot be given, as it is not possible to divide the old outlay upon them between the different portions of the works. The figures show the cost of the main and branch canals only exclusive of head-works, distributaries and drainage works, &c.: they give the actual cost of the canals, and do not include the charges for establishments, tools, &c., for which about 25 per cent. would have to be added.

Branch canals and distributaries may be designed on the same general principle as main canals; that is, that they shall be capable of carrying the discharge which is necessary during the period of maximum demand. But some branch canals, and all distributaries, are subject (or should be subject) to the system of rotation or *tatils*, which has been described in the last chapter; and this is a factor which has to be taken into consideration in settling the capacity of a distributary, as a larger channel is, of course, necessary when tatils are enforced than when a system of constant flow is permitted. If the system of tatils and the

COST OF MAIN AND BRANCH CANALS.

Canal.	Miles of Main and Branch Canals.	Cost.	Cost per Mile.
		Rs.	Rs.
Bengal :—			
Orissa Canals ..	252	92,33,794	36,642
Midnapore Canal ..	72	35,15,622	48,828
Sone Canals	367	102,67,357	27,976
N.-W. Provinces :—			
Ganges Canal ..	437	166,77,253	38,163
Lower Ganges Canal	557	168,47,269	30,246
Agra Canal	109	43,93,742	40,309
Betwa Canal	168	16,55,180	9,852
Punjab :—			
Bari Doab Canal ..	362	94,44,744	26,090
Sirhind Canal ..	542	177,27,159	32,706
Chenab Canal ..	91	25,80,623	28,358
Sidhnai Canal ..	58	3,45,804	5,962
Swat River Canal ..	22	21,62,973	98,316

duty of water in the distributary are both known, the capacity of the channel is easily determined. Thus, taking the cases of distributaries V and Z in the sketch on page 242, distributary V irrigates 4750 acres, and distributary Z 5700 acres of khareef crop, and the duty of water at the head of each is considered to be 75 acres to a base of 15 days. V is open for 10 days in 14, and Z for 12 days in 14, as shown in Tatil Table No. 1, but a period of 15 days may be selected in each case during which V is only open for 10 and Z for 12 days. In order to gauge the required discharge of the distributaries, the duty of each must be reduced to the base of 10 and 12 days respectively. A duty of 75 acres to a base of 15 days is equivalent to 5 acres to a base of 1 day or 50 acres to a base of 10 days, and 60 acres to a base of 12 days. The required discharges are therefore—

In the case of distributary V $= \frac{4750 \text{ acres}}{50} = 95$ cubic feet a second.

" " " $Z = \frac{5700}{60} = 95$ cubic feet a second also.

The latter distributary requires the same discharge for 5700 acres as the former does for 4750, simply because it runs for a longer period.

The duty of 75 acres to a base of 15 days is equivalent ($S = \frac{B}{D} \times 23{\cdot}8$, page 223) to a depth of 4·8 inches in the field, if the whole discharge reaches it, or to about 4 inches if only 10 per cent. of the discharge of the distributary is lost by absorption, &c., on its way to the field. In cases where only one crop is grown—say rice—and when the depth of the watering required in a given time during a period of pressure is known, it is easier perhaps to work on the basis of the volume required in the time for the area to be irrigated. Thus: a distributary has to irrigate 5000 acres of rice crop, and it is considered necessary at a time of maximum demand to place 4 inches of water in all the fields during a period of 12 days; then (by Formula III., p. 223) the required discharge is $= \frac{A\ S}{B \times 23{\cdot}8} = \frac{5000 \times 4}{12 \times 23{\cdot}8} = 70$ cubic feet, which must be increased by the estimated loss in the village channels and in the distributary, an amount which may vary from 10 per cent. to 50 per cent. according to the length of channel, nature of soil, &c.

The dimensions given to distributaries in Upper India are usually determined as follows:—

T = gross tract commanded by a distributary.

t = area of unculturable land, i.e. roads, village sites, waste land, &c.

b = proportion of the culturable land which is to be irrigated (varies from 1·0 to 0·20) during the year.

k = proportion of area to be irrigated which is cultivated in khareef crops.

Then

$T - t$ = culturable area commanded by the distributary;

and

$T - t \times b \times k$ = area of khareef crop to be irrigated.
= A of Formula III., page 223.

So that the discharge of the distributary (x) has to be

$$x = \frac{A}{D} = \frac{(T - t)\, b\, k}{D}.$$

The values given to b and k vary according to the conditions of cultivation in different localities. In one case in the Punjab, b is taken as 0·25 and k as 0·4. That is, only one-quarter of the culturable area

commanded by a distributary is allowed to be irrigated in the year, and two-fifths of this area is considered to be khareef crops. D is taken as 60, so that—

$$x = \text{discharge of any distributary in continuous flow} = \frac{(T - t) \times 0{\cdot}25 \times 0{\cdot}40}{60}$$

$$= \frac{T - t}{600},$$

and the capacity of the distributary has to be increased beyond this in proportion to the tatils which are to be enforced. In another case in the Punjab, the discharge of a distributary (for continuous flow) is taken as $\frac{T}{760}$: which is equivalent to $\frac{T - t}{570}$ (if t is taken at 0·25 of T as is often the case). On the Ganges Canal in the North-West Provinces a further factor—

c = area already irrigated by wells in the tract commanded by a distributary—

is taken into consideration: the value of b is taken as 0·8 and $k = 0{\cdot}5$ and:—

The area of khareef crop to be irrigated is $= (T - t) k b - c$

$$= (T - t) \times 0{\cdot}4 - c.$$

A duty of 70 acres was taken in most cases, so that:—

$$x = \text{discharge of any distributary (for continuous flow)} = \frac{(T - t) \times 0{\cdot}4 - c}{70}$$

and where c was $= o$ the discharge of a distributary became $\frac{T - t}{175}$.

In the Sone canals in Bengal, b has usually been taken as 1·0 and k as 0·5, and a duty of 80 acres for the season was assumed, so that—

$$\text{The discharge of a distributary (for continuous flow) became} = \frac{(T - t) \times 0{\cdot}5}{80}$$

$$= \frac{T - t}{160};$$

but, of late years the duty has been taken at a lower figure for the reasons explained in Chapter XV., and some distributaries have been constructed on the basis of a duty of 50 acres which is a much more correct figure in this case. In all these examples the base of the duty has not been expressed, and the formulæ rather produce the impression that it is necessary to have 1 cubic foot of water running in a dis-

tributary for the whole season to mature 60, 70, or 80 acres, as the case may be, of khareef crops. This is not the case, and the "duties" really are applicable to the periods of pressure, or, say, to bases of about 15 days. In these examples, too, the result is in all cases for continuous flow, and where tatils are enforced, the capacity of the distributary is increased in proportion to the closure which is contemplated. In Bengal (on the Sone canals), closures of entire distributaries for half-time were provided for, and the channels were cut to carry twice the discharge given above. This period of closure is excessive: 5 days' closure in 15 is sufficient. In the Sirhind Canal distributaries, no closures are provided for, and tatils are enforced on the minor channels only.

A distributary which is designed for the kharcef demand is always more than large enough for the rabi crops, for the areas of the two crops are generally taken in Upper India as about the same, and the "duty" of water in the cold season in any distributary is generally at least double the duty in the khareef season.

This variation in the discharge of a distributary introduces some difficulties in the grading and section of the channel: it is generally better to grade the channel mainly with reference to the rabi discharge, so that the surface of the water when running in low supply may be on the average, about 1 foot above ground-level. Distributary slopes are usually cut at 1 to 1, but where there is silt in the water the sides generally silt up to slopes of about $\frac{1}{2}$ or $\frac{3}{4}$ to 1, so that it is best to base all calculations of discharge on those reduced slopes. These silt berms are a great protection against percolation and absorption, and they should never be cut away unless the discharge of a distributary is injuriously affected by them.

In Appendix VII. the detailed rules for the preparation of distributary designs, which are in force in the Punjab, are given. In that province the government does not only construct the larger distributaries, but the minor channels are made from them into each village, so that the villagers never have to construct their own channels beyond the boundaries of their own ground. A "minor" is defined as a channel carrying less than 10 cubic feet a second: if a larger discharge has to be carried the channel is classed as a branch distributary. The rules for the construction of these "minors," which are suitable for all channels—whether constructed by government or by the villagers—are given in Appendix VIII. In the sketch on page 242, these "minors" are shown on distributary W. These channels in Bengal and in the North-West Provinces have generally been constructed by the villagers

themselves, or at the expense of the villagers who have rights of ownership in them. The more perfect these small channels are the greater "duty" can be obtained for the water, but it is often a matter of great difficulty to induce the villagers to make them properly, or, if they do make them, to maintain them in a proper condition. This is more especially the case where large tracts of rice land are irrigated, for it is so easy to pass the water from field to field when every field is more or less submerged, and this method is so widely practised by the cultivators when they mature the rice crops by the rainfall only, that it is difficult to get the villagers to see any advantage in the small channels: indeed in many cases there is no advantage when there is an unlimited supply of water; but, when the supply is limited, there is no question that a larger area can be efficiently irrigated with the same supply. In some rice tracts—such as those irrigated by the Midnapore Canal in Bengal—floods occasionally occur which are very destructive to small channels, so much so, that in more than one case, they have completely disappeared in a few years. In Madras, where rice is mainly cultivated, small village channels are rarely made, and the irrigation is effected by a system of wide-spread flow from field to field. In Orissa and Midnapore also, where rice is the main crop, it has been found impracticable to enforce the construction of village channels from the distributaries, and the system of wide-spread field to field irrigation is acknowledged. Under this system villages which are near the distributaries are well protected, but, in a time of pressure, those which are far from distributaries, and can only obtain water through intervening villages, are in a very unfavourable position. The practice of this method of irrigation has made it necessary to introduce a complicated system of supplying water, under which a distant village is refused a supply unless either the intervening villages are leased for irrigation or the distant village will construct the necessary channel.

In the Chenab Canal extension project in the Punjab, the following are the rates allowed in the estimate for the distributaries :—

	Rupees per mile.
Channels discharging more than 150 cubic feet per second ..	4500
Channels discharging from 30 to 150 cubic feet per second ..	2500
Channels discharging less than 30 cubic feet per second	1250

The following statement shows the cost of distributaries, per mile and per acre irrigable, on some of the chief perennial systems of Upper India. The figures are the actual cost of the works, including land, but

they do not include the charges for establishment, tools, &c., for which an addition of about 25 per cent. must be made :—

COST OF DISTRIBUTARIES.

Canal.	Number of miles of Distributaries.	Cost.	Cost per mile.	Cost per acre irrigable.
		Rs.	Rs.	Rs.
Bengal :—				
Orissa Canals	765	18,00,348	2,353	7·1
Midnapore Canal	283	8,91,825	3,151	7·1
Sone Canals	1,211	43,71,065	3,609	4·3
N.-W. Provinces :—				
Ganges Canal	2,523	48,26,330	1,912	3·2
Lower Ganges Canal ..	2,097	34,65,893	1,652	4·1
Agra Canal	565	10,18,937	1,803	6·7
Betwa Canal	341	3,89,021	1,140	3·2
Punjab :—				
Western Jumna Canal ..	911	12,55,270	1,377	2·2
Bari Doab Canal	1,048	21,54,215	2,055	4·0
Sirhind Canal	4,385	50,04,606	1,141	6·4
Chenab Canal	283	7,43,094	2,625	5·0
Sidhnai Canal	146	1,89,278	1,296	1·8
Swat River Canal	140	5,18,662	3,704	4·3

The small heads by which water is drawn from a distributary into a village channel are called outlets. Plate XCII. shows various forms of these which are in use. In some few cases, where large areas are irrigated from the same outlet, masonry vents are constructed, but as a rule outlets in distributaries and "minors" are made with circular pipes: these vary in size from 3 inches to as much as 12 inches, but in a majority of cases 6-inch pipes are found most convenient, and if one of these is not sufficient two or more are fixed. The outlets in many cases are closed by a clod or piece of turf only, or by a wooden plug, but where tatils have to be enforced, with perhaps some difficulty, locked valves or shutters of some kind have to be fitted. Some of these are shown on the plate.

Economy of water results from a careful restriction of the size of

the outlet to the area under irrigation from it. It has already been mentioned that there is probably more loss of water in village channels than in other parts of an irrigation system; this loss is enormously increased when extravagant outlets are provided. This is more particularly the case in rice irrigation, where the cultivators have generally many opportunities of passing off superfluous water unnoticed; if the outlets are larger than is really necessary, a cultivator will often allow water to run through his fields for no good purpose, but if his outlet is proportionate to his real needs he is more careful of the supply, and will thus leave more water available for his neighbours. A good general rule for the size of outlets is that in the khareef season they should be capable of delivering 4 inches of water in depth over the area irrigable in a period of 10 days, and in the rabi season they should be capable of giving a depth of $2\frac{1}{2}$ inches in 15 days. The discharge of an outlet varies, of course, with the head upon it, and the head varies with the supply in the distributary. In the Sone canals in Bengal, where large tracts of rice have to be irrigated, observations are recorded, at times of pressure, of the actual difference in level between the water in the distributary and in the channel below the outlet, with the object of recording facts to aid in the proper calculations of the outlets, but in most cases it is usual to assume a moderate head of about 6 inches in the rabi season, and to base the size of the outlets on the hypothesis that the head is constant. A rule has been in force on the Ganges Canal that each square inch of vent age is sufficient for $1\frac{1}{4}$ acres of rabi when tatils of half time are allowed. It will be found that this rule agrees fairly well with the general one which has been given above. The discharge from pipe outlets is usually calculated from the formula used for orifices (Formula I., Appendix V.), which is sufficiently accurate for practical purposes, but experiments have shown that it is well to give a value of 0·6, or even 0·5, to the coefficient c in the formula, as the pipes are rough, and often not very truly laid.

It is generally agreed that it is best, as a rule, to place the outlets in distributary banks at the level of the bed of the channel, except in the upper reaches of large distributaries, where a sufficient head of water can be relied upon, and that the upper edge of the vent should, even in such cases, be 2 feet below the full supply level. The rule which is sometimes used of placing the outlet at a fixed depth below the full supply level, often results in inconvenience when some particular crop—sugar-cane, for instance—requires a very small supply of water when the distributary is low. The objection to placing outlets at the

bed level is the difficulty which arises in closing them unless they have sliding shutters in more than 2½ feet of water.

In connection with every irrigation system it is necessary to construct a series of drains to carry off the surplus water after it has completed the irrigation of the crops. If this important element in an irrigation scheme is neglected, the land may become waterlogged and sterile. The extent to which it is necessary to construct drainage channels varies greatly with the nature of the soil, with the proportion of khareef crops, and with the levels of the country. In many tracts the natural drainages are clearly marked, and lie sufficiently below the irrigated fields to effect the purpose without artificial means, especially if the subsoil is sandy. In other parts, where the natural drainages are ill defined, and very probably cultivated, it is necessary, especially if the soil be stiff, to acquire a strip of land in the low ground lying between two irrigation channels, and construct a drain to carry off surplus water to the nearest stream. Plate VI., page 14, shows some of these drains in the Godaveri Delta system. In India such works, where they have to be constructed, must, in most cases, be designed to carry off a

COST OF DRAINAGE OF PROTECTIVE WORKS.

Canals.	Cost of Drainage and Protective Works.	Cost per acre irrigable.
	Rs.	Rs.
Bengal :—		
Orissa Canal	16,80,774	6·6
Midnapore Canal	3,56,132	2·8
Sone Canals	7,88,988	0·7
N.-W. Provinces :—		
Ganges Canal	10,02,010	0·7
Lower Ganges Canal ..	3,51,665	0·4
Agra Canal	87,043	0·5
Eastern Jumna Canal ..	5,54,152	1·7
Punjab :—		
Western Jumna Canal ..	4,86,228	0·8
Bari Doab Canal	1,10,417	0·2
Sirhind Canal	10,60,127	1·3

portion of the rainfall in addition to the surplus water from irrigation, and they vary in capacity from 2 up to 50 or even 80 cubic feet per second per square mile, of which only a very small portion is water from the canals. In Egypt, where there is practically no rainfall, it is usually considered that provision should be made for draining off 8 cubic metres (283 cubic feet) per day from each acre, which is only about 2 cubic feet per second per square mile. Drainage works are usually carried out gradually as irrigation developes, and as the necessity for them in certain parts becomes manifest.

The foregoing statement shows the cost of drainage works in some of the principal perennial canals of Upper India. The reason of the high cost of the works in Orissa is mainly because the figures include the cost of heavy protective embankments, which exclude floods from the irrigated tracts. In the other cases the figures are almost exclusively for drainage works alone. The figures give the actual cost of the works, including land, but exclusive of charges for establishment, &c., for which about 25 per cent. has to be added.

CHAPTER XVII.

REVENUE AND ADMINISTRATION.

Irrigation Revenue—Miscellaneous Revenue—Occupier's Rate—Owner's Rate—Enhancement of Land Revenue due to Canals—Administration—Assessment of Irrigation Revenue—Cost of Revenue Management—High Cost of Administration in Bengal—Cost of Working Expenses.

THE revenue which is earned by the irrigation works of India comprises, first, that which is derived from the use of the water for the crops, which is called "Irrigation Revenue" proper; and, secondly, the "Miscellaneous" Revenue which is derived from many services, rendered by an irrigation system, which are not immediately connected with the watering of crops.

The Miscellaneous Revenue is about 6 or 7 per cent. only of the total: it consists chiefly of returns from navigation, sale of water-power for mills, plantations, and to a small extent from water supply of towns, rents, sale of fruit, &c. The returns from navigation are considerable in Bengal, where the three chief irrigation systems are navigable and do carry some traffic,* but in the other provinces they are insignificant. Sale of water-power is considerable (about Rx.† 15,000) in the Punjab, where small mills for grinding corn are erected at many of the canal falls, but is inconsiderable elsewhere. The revenue from plantations is best in the North-West Provinces (about Rx. 15,000) where there are extensive areas, on the banks and on the surplus lands connected with the canals, which are excellently planted with revenue-producing trees.

The "Irrigation Revenue" proper, which is derived entirely from the watering of crops, is assessed in ways which vary according to conditions of cultivation, and according to the method of assessment of the "Land Revenue" in the different provinces. This "Land Revenue" forms the greater portion of the public revenues of India.

* The navigation returns from the Midnapore Canal are large.

† This symbol Rx. denotes "tens of rupees," that is the old conventional pound sterling of the days when ten rupees were equal to one pound

It is a tax or rent charged by Government on all occupied lands, and is collected in some provinces directly from the ryots or occupiers of the fields, and in others from the zemindars or landowners who collect their own rents from the ryots. The Irrigation Revenue can, in some cases, be very conveniently amalgamated with the Land Revenue, indeed it is sometimes difficult to discriminate between the two. In Sind, for instance, where crops are grown only on irrigated land, and where land without water is valueless, the assessment of both land and water revenue is made in one sum, and the custom is to credit the accounts of the irrigation works with 90 per cent. of the gross collections. In Madras also no separate charge is made to the cultivator for the water he uses in irrigating his crops, but both land and water revenue are assessed and levied together as "wet" land revenue, and a portion of the amount is credited to the irrigation works as the share due to them for their agency in carrying the water to the fields, the remainder going to the credit of "Land Revenue."

In the three provinces of Upper India, and in Bombay, the Irrigation Revenue is not assessed with the Land Revenue, but is distinct from it, and, although it is usually collected by the same establishment, it is, in nearly all cases, assessed by the Irrigation Officers and not by the Civil Department which makes the assessments and collections of the Land Revenue. In these provinces Irrigation Revenue consists of (1) Occupier's rate, (2) Owner's rate, and (3) Enhancement of land revenue due to the canals. The Occupier's rate (1) is the water-rate payable by the *ryot*, the tenant and actual cultivator of the soil; it is assessed on the area irrigated, and varies according to the nature of the crop irrigated.

The Owner's rate (2) and the Enhancement of Land Revenue (3) are, essentially, the same thing. They are the share due from the zemindar or landowner on account of the enhanced value of his property due to the irrigation works. The rate is called an Owner's rate when it is assessed on the owner separately from the land tax, but, when this tax is revised, from time to time, at the settlement periods, the Owner's rate may be amalgamated with the land tax, and then the share due to the irrigation works is credited to them as "Enhancement of Land Revenue."

It might be thought that if the ryot or occupier was charged a sufficiently high rate for irrigation, that it would be simpler to collect the entire Irrigation Revenue from him,* but, owing to a variety of causes,

* 'Note on the basis on which Irrigation Revenue is calculated,' by Col. H. A. Brownlow, R.E., formerly Inspector-General of Irrigation in India, 14th Feb., 1884.

it is, in almost every case, impossible, with due regard to extension of canal irrigation, to charge so high a rate for the water to the cultivator as to preclude the zemindar (or landowner) from reaping some advantage from the introduction of canal irrigation by a rise in the rent, which he collects from the cultivator, for the canal irrigated land. Nor, indeed, is it desirable that this should be done. In order, for instance, to do this effectually, it would be necessary to drive a separate bargain with each cultivator for each crop grown under canal irrigation, which would be practically impossible. In order to secure rapid and economical assessment of the canal revenue, canal rates must be uniform for each class of crop, and cannot take into consideration differences in the quality of the crops watered, differences arising from the varying nature of the soil, style of cultivation, and other causes independent of the canal. But all-round crop and acreage rates, applicable to wide areas and to various soils and classes of cultivators, must be kept at a comparatively low average, in order to avoid undue pressure on the poorer soils and unfavourably situated localities. Therefore rents invariably rise more or less, sooner or later, after the introduction of canal irrigation, and the Government steps in, by means of the Owner's rate, to claim its share in the profits which are being reaped by the landlord from the operation of works constructed by the State.

The Land Revenue is adjusted from time to time by a revised settlement of the land tax, a rent which is paid to Government. This is the case in all provinces except Bengal, in which the land tax was crystallised for ever by the famous "Permanent Settlement" of Lord Cornwallis. Owner's rate is theoretically a special rate imposed, during the currency of a settlement, on landlords, in order to secure the Government share of the increase in rental due to canal irrigation, and is limited, in most cases, to half the difference between the rent paid before and that paid after the introduction of this irrigation. On the expiry of a settlement and introduction of a new one, the Owner's rate, or a certain portion of it, may either be amalgamated with the Occupier's rate, or, if the latter be maintained constant, the whole of the Owner's rate may be merged in the land revenue, and appear as an indirect credit to the Irrigation Works as "Enhancement of land revenue due to canals."

"The decision of the question of the extent to which the Owner's rate should be amalgamated with the Occupier's rate would be guided by a consideration of the extent to which the available supply of canal water is used for irrigation. Hitherto the Owner's rate has been imposed in a rough-and-ready fashion (either as an all-round rate, or as a rate

proportioned to the Occupier's rate) on land actually irrigated during each year. This system of assessment is confessedly incorrect, because the assessment does not take cognisance of the main principle on which rents of canal-irrigated land rise. They rise, not so much on account of the actual use of canal water, as on account of the advantage of being able to take canal water upon necessity arising. This is sufficiently proved by rents rising on all land irrigable by a canal, not alone on that actually irrigated. It is obvious that Owner's rate, assessed in the manner above described, does not touch the enhanced rental of much canal irrigable land until this land comes, in course of rotation, to be actually irrigated; and when the rate is imposed in this manner, it is regarded simply as an addition to the Occupier's rate, and, as such, is immediately transferred by the landlord to the cultivator. If therefore the amalgamated Occupier's and Owner's rate is found to press so heavily on the poorer soils and crops as to exclude them entirely from the benefit of canal irrigation, and prevent the full utilisation of the available supply of canal water, it is plain that too high a direct charge is being made for the water. The Owner's rate cannot in such case be advantageously incorporated with the Occupier's rate, except perhaps to a certain extent, and it will be far more profitable, both to the State and to the community, to keep the Occupier's rate just low enough to ensure the fullest use of the canal water, and to look to the Settlement Officer to secure the Government share of profits arising from the rise in rents of lands of the better class, by periodical assessments of land revenue based on consideration of the increase which has actually occurred."*

One of the reasons for the unfavourable financial results displayed by the canals in Bengal† is that up to the present time no Owner's rate has been assessed and no Enhancement of Land Revenue has been made. Unfortunately the areas watered by the Sone and Midnapore canals lie within the tract where the Permanent Settlement has finally fixed the Government Land Tax, and it is impossible for Government to obtain the revenues from the Irrigation Works which are really their due. The result of this has been a very large and unearned increment to the wealth of the zemindars or landowners. In Orissa the settlement is not a permanent one; a revision of it is now in hand and will be completed in 1896, when the increased rents, which the landowners have obtained from the cultivators in consequence of the irrigation works, will be con-

* 'Note on the basis on which Irrigation Revenue is calculated,' by Col. H. A. Brownlow, R.E., formerly Inspector-General of Irrigation in India, 14th Feb., 1884.

† See Chapter XVIII., pages 275 and 276.

sidered in assessing the new land tax, a portion of which will, it is understood, be credited to the Irrigation Revenue as share of Enhanced Land Revenue. The Orissa canals are a good instance of the necessity of dividing the incidence of the water rates between the actual cultivator and the landlord. The water rates in Orissa are the lowest in India, and are collected with more difficulty than those of any other irrigation system. But, at the same time, the rents, both of lands irrigated from the canals and of those which are irrigable from it, have risen largely since the works were opened. Some portion of this increment is due to other causes than irrigation, but there can be no doubt that the larger portion of it is due to the security which is given by the existence of the works.

The assessment of Irrigation Revenue is made, in Upper India, under the direction and control of the officers of the Irrigation Branch of the Public Works Department; these are the same officers—Engineers—who maintain the works in an efficient state, and control the distribution of the water to the fields. A Chief Engineer, who is usually also Secretary to the Local Government in the Public Works Department, is at the head of the establishment of the province; under him are Superintending Engineers of "circles" who have jurisdiction over areas which may include from half a million to a million acres of irrigation: next come the Executive Engineers, who control "divisions" which vary in size up to areas which may include as much as 200,000 acres of irrigation. The Executive Engineer is the officer who is responsible for the proper assessment of the Irrigation Revenue, and generally for the collection of the Miscellaneous Revenue earned by the canals: he is also responsible for the repairs of the works, for the preparation of projects for the improvement of his division, and for the proper regulation and distribution of the canal water. He is assisted by a large establishment of Government officials, chiefly composed of natives of India, who live in the various "sub-divisions" and "sections" into which the division is divided.

The establishment of the Public Works Department is divided in some provinces into two distinct branches, one of which deals almost exclusively with the Irrigation Works, and the other with the other public works of the province. But in some cases the irrigation officers undertake the charge of all the public works, except the railways, which lie in the districts under their charge, so their duties are often very multifarious.

The system of assessment of the Irrigation Revenue varies on

different canals, but substantially the assessment is made in the following manner by the officials named :—

The Patrol, who is an intelligent peasant, capable of reading, writing, and making rough measurements, visits and inspects the irrigation in his beat at frequent intervals, and records in his register (*shudkhar*) each field as it is irrigated, with certain statistics concerning it. His register is the primary record of irrigation. With the help of this register :—

The Ameen, who is a superior man who can survey and measure land accurately, prepares a measurement register (*khusrah*) of the areas irrigated. This document may be the result either of actual measurement with a chain, or it may be prepared from the village maps, which, where they are available, give the area of each field and other statistics. The Ameen's measurement-sheet is usually attested by the signature of the head-man of the village, by the village accountant (the *putwaree*), and often by other persons who are interested, in token of its correctness. From this document the demand statement (*khationcc*) is prepared, either at the time of the measurement by the Ameen himself, or subsequently in his office, with the help of a number of native writers (*mahurirs*). The work done by the Ameen is subjected to scrutiny by :—

The Zilladar, who is a step higher in official rank than the Ameen, and who understands the law and procedure better. This official makes measurements to check the work of the Ameens, and generally supervises the assessments. He hears and decides questions which are preferred by the cultivators regarding their irrigation and assessment. In some cases there is another official :—

The Deputy Collector, who is a subordinate judicial official of some standing in the Civil Department, is appointed, in the North-West Provinces, to supervise the work of a number of zilladars, and to hear suits in court which may arise in connection with irrigation. But he rarely interferes with the assessment papers.

The Sub-divisional Officer, who is generally an Assistant Engineer, but in some cases a Subordinate in the Public Works establishment, has the general supervision of all these lower officials. He is a gazetted officer, on whom the real responsibility of the assessments rests. He hears complaints and practically decides most cases in which claims are made for remissions. He is almost incessantly travelling about over the irrigated fields, listening to the complaints and wishes of the cultivators. He countersigns the demand statements (*khatioucs*) after

they have been worked out by his subordinates, and forwards them to the Executive Engineer.

When the demand statement has been finally approved, it is sent by the Executive Engineer to the collector of the district and the money which is due is recovered by that officer.

The Patrol wears a uniform and is an important person among the cultivators who irrigate from the canals. He has many duties to perform, in connection with the irrigation, which vary in different canals; in some cases he sees to the distribution of the water, while in others he only concerns himself with the record of areas irrigated. His pay varies from 5 to 10 rupees a month, and he deals with 1500 to 3000 acres of irrigation. The Ameen draws from 10 to 25 rupees a month, and will generally deal with 7000 to 10,000 acres of irrigation. The Ziliadar draws from 50 to 100 rupees, and will supervise 30,000 to 50,000 acres. The Deputy-Collector will probably deal with 80,000 to 120,000 acres, and his pay will be from 200 to 300 rupees.

It may seem that the establishment which is employed is a formidable hierarchy. The tendency in India, there is no doubt, is to multiply officials and divide responsibility to too great an extent, but the work of the assessment of irrigation revenue is extremely laborious, and the documents are very bulky, in consequence, chiefly, of the small area of land held by each cultivator. In Orissa, for instance, which is, however, rather an extreme case, the average demand from each cultivator is less than one rupee and a half. The labour and difficulty both of assessment and collection, may be imagined when such petty sums have to be collected from some 200,000 men distributed over a large tract of country.

The cost of the working and management of Indian canals is shown in great detail in the revenue accounts of the different works: the total charges are primarily divided into the sub-heads, "Revenue Management," "Maintenance of Works," and "Indirect Charges." The first sub-head includes the cost of all establishments employed (both in the Public Works Department and, under the Collector, in the Civil Department) in the assessment and collection of Canal Revenues. The following statement shows the cost of "Revenue Management" in the chief irrigation systems of the Upper Provinces.*

This table shows that in the N.-W. Provinces and the Punjab the cost of revenue management averages about 20 per cent. of the revenue collected, but in Bengal it is from 30 to 60 per cent. The cost in

* Based on Form 1 C of the Revenue Reports of the provinces named.

COST OF "REVENUE MANAGEMENT."

System.	Average incidence of Water Rates per acre, based on the average of five years.	Cost of Revenue Management.*			
		Average of five years.		In 1889-90.	
		For each rupee of Water Rates collected.	For each acre of land irrigated.	For each rupee of Water Rates collected.	For each acre of land irrigated.
	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.
Bengal—					
Orissa	1·14	0·59	0·71	0·55	0·59
Midnapore	1·51	0·39	0·59	0·31	0·53
Sone	2·47	0·28	0·74	0·30	0·80
N.-W. Provinces—					
Ganges	2·85	0·16	0·48	0·17	0·37
Lower Ganges	2·46	0·22	0·54	0·19	0·49
Agra	3·27	0·14	0·48	0·13	0·36
Eastern Jumna	3·02	0·12	0·38	0·13	0·30
Punjab—					
Western Jumna	2·44	0·27	0·67	0·23	0·44
Bari Doab	2·40	0·17	0·41	0·18	0·43
Sirhind	1·96	0·16	0·31	0·16	0·42

Bengal is, no doubt, very high, but it is obvious that, to a considerable extent, the cost of management must vary inversely as the incidence of the water rate, and directly as the area irrigated, for the work done is practically the same, whether the rate charged for the water is high or low. It has already been mentioned (page 262) that the Bengal rates are abnormally low, partly on account of the action of the Permanent Settlement which prevents the imposition of an "owner's rate," so there are additional reasons why the cost of the management in that province should be gauged by the figures given in the column "For each acre of land irrigated," and not by a percentage on collections. But even when this is considered it must be admitted that the cost in Bengal is very high. This is partly due to the fact that, owing mainly to the physical difficulties inherent in the assessment of irrigation revenue on large tracts of rice land, the system of taking

* Exclusive of charges on account of navigation.

formal leases and issuing permits, which is required by the law of Bengal, is more cumbersome than the procedure in the other provinces, where, practically, a cultivator irrigates at his pleasure and pays on whatever acreage he waters. But the high rate of Bengal management is also to some extent due to the fact that the cultivator of Bengal is really more difficult to deal with than his neighbour in the other provinces, as is indicated by the far larger number of untenable claims for remissions and frivolous complaints of assessments which are preferred in Bengal.

The Accountant-General* of the Public Works Department has prepared the following statements, showing the percentages of the cost of "Revenue Management" on the revenue collected, and the Working Expenses per acre irrigated in the case of all the Major Works† in the different provinces during the five years ending 1890-91 :—

PERCENTAGE OF "REVENUE MANAGEMENT" ON REVENUE COLLECTED.

Provinces.	1886-87.	1887-88.	1888-89.	1889-90.	1890-91.
Bengal	24·4	38·2	30·7	28·5	33·2
N.-W. Provinces	13·7	14·7	13·6	13·5	14·3
Punjab	13·9	13·7	15·0	15·1	13·0
Madras	10·2	10·3	10·4	10·3	10·3
Bombay (including Sind) ..	11·5	11·3	10·1	11·1	11·5

TOTAL WORKING EXPENSES PER ACRE IRRIGATED.

Province.	1886-87.	1887-88.	1888-89.	1889-90.	1890-91.
	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.
Bengal	3·2	3·0	2·4	2·4	2·5
N.-W. Provinces	1·7	1·6	1·7	1·4	1·4
Punjab	1·3	1·2	1·1	1·1	1·1
Madras	0·7	0·8	0·7	0·7	0·8
Bombay (including Sind)‡ ..	0·9	0·8	0·7	0·7	0·8

* Note by R. G. Macdonald, Esq., Acct.-Genl. P. W. Dept., upon the accounts of Revenue and Expenditure of Irrigation Works in India, 1890-91.

† For a definition of "Major Works," see Chapter XVIII.

‡ The working expenses in Bombay proper are the highest in India, but when Sind is included they are as moderate as those in Madras, as the charges in Sind are low.

The statistics of the cost of "Revenue Management" must not be confused with the "Working Expenses," which show the entire charges, including revenue management, of the maintenance, working, and management of the canals. The percentage of "Working Expenses" to Revenue is shown in the following statement* :—

PERCENTAGES OF WORKING EXPENSES ON GROSS REVENUE.

Bengal	96·1	136·8	101·7	89·0	100·3
N.-W. Provinces	40·2	44·2	45·3	44·2	39·3
Punjab	42·0	40·0	42·5	39·9	35·0
Madras	21·9	21·9	21·3	20·9	22·6
Bombay (including Sind) ..	41·1	39·4	33·2	34·5	35·7

The very heavy cost of working expenses in Bengal has frequently received the attention of Government. It is partly due to the causes already explained and partly to the fact that the irrigation systems do not nearly work up to their full power, that is, the areas irrigated are a smaller percentage of the areas irrigable than in other provinces, so that establishment and other permanent charges bear more heavily on the results. Another cause is the large amount of dredging and silt clearance which is necessary on the Sone and Midnapore canals; and a third is the more complex system of the assessment and collection of Canal Revenue, which necessitates larger establishments. Madras and Sind stand out prominently in these returns as provinces in which the administration of irrigation works is most economical.

* From the same Note by the Accountant-General.

CHAPTER XVIII.

COST OF IRRIGATION WORKS AND THE FINANCIAL AND AGRICULTURAL RESULTS OBTAINED FROM THEM.

General Classification—Capital Cost of Productive Works—Major Works (A)—Gross Profit on Productive Works—Progress of Productive Works—Protective Works—Major Works (B)—Minor Works (A)—Profits from Minor Works (A)—Extent of Minor Works (A)—Minor Works (B)—Agricultural Results—Protection from Famine—New Projects—Gross Revenue derived by Government.

THE irrigation works of India are primarily divided, in all statistical returns, into two main classes—the Major Works and the Minor Works. This classification is not entirely a logical one, as there are some of the minor works which are of more importance than some of the major ones; but, generally speaking, it may be said that the major works are the more important ones, which have been, in most cases, entirely constructed, or largely reconstructed, by the British Government; while the minor works are generally of smaller pretensions, and in many cases they are modifications or improvements of irrigating systems which existed in an imperfect state before the country in which they lie was annexed.

Each of these main classes is again subdivided into two secondary ones, thus:—

Major Works:—(A) Works of which the capital has been provided from borrowed money (Productive Works). (B) Works of which the capital has been provided out of the general revenues of India (Protective Works).

Minor Works:—(A) Works of which capital and revenue accounts are kept. (B) Works of which no capital accounts are kept.

The expenditure on the Minor Works is entirely from the general current revenues of India, and in no case from borrowed money.

The Major Works (A) have for some years past been styled "Productive Public Works"; and they were previously known as "Extraordinary Works," that is, works not constructed from "Ordinary" or

current revenues of India. There are 35 systems in this class. Before a project can be sanctioned for construction from borrowed money as a Major Work (A), it is necessary that there should be good reason to think that it will provide a net revenue equal to or greater than the interest which Government has to pay on the money borrowed for its construction. The test, in fact, which is applied to all projects for works of this class, is a purely commercial one; it is considered essential that borrowed money should only be expended on works which are likely to be remunerative.

The Major Works (B) are six in number.* They are the works generally known as "Protective Works" which will not stand the commercial test which is applied to the Major Works (A), that is, the net revenue derived from them is not likely to cover interest on the capital expended. They are works which it was considered desirable to construct in order to produce food grains as a protection against famine. These works are theoretically constructed from the "Famine Relief and Insurance Fund" which was formed in 1881–82, the capital cost of the works is provided from the general revenues of India, that is, the expenditure is charged as part of the annual expenditure of the Empire.

The Minor Works (A) comprise 54 systems in operation; besides these there are 11 small works under construction and several in abeyance. Some of these works are old tanks and inundation canals which have been taken over, improved, and worked by the British Government; others are new works entirely constructed by the British Government, but which do not fulfil the conditions of the two classes of Major Works above described. The majority of the Minor Works (A) are works which had been constructed before the system of constructing irrigation works from borrowed funds had been introduced, otherwise some of them would have been classed as Major Works (A).

The Minor Works (B) are extremely numerous and generally of small extent individually; the great majority of them are old works, mostly tanks in the Madras Presidency; there is no record of their original cost.

Major Works (A).

The 35 works of this class which are either completed or under construction, have actually cost 27 millions of Rx.,† as compared with

* Excluding two works in abeyance.

† The symbol Rx. denotes ten rupees, or the old conventional pound of ten rupees to the pound.

28½ millions of Rx. which was the estimated cost of the complete projects. The details, by Provinces, are shown in the following statement:—

MAJOR WORKS (A).—PRODUCTIVE WORKS.

Province.	Number of Works.	Capital expenditure including indirect charges.	Sanctioned estimates for the complete projects.
		Rx.	Rx.
Bengal	4	6,167,319	7,271,964
N.-W. Provinces	4	7,440,501	7,435,639
Punjab	7	5,886,837	6,717,374
Madras	9	5,627,387	* 6,465,796
Bombay	7	1,054,612	1,056,093
Sind	4	858,875	881,698
Total	35	27,035,471	29,828,564

Out of these 35 works, 32 are in operation, and 3† are in course of construction. There is another work in the Punjab called the Jhelum Canal, estimated to cost Rx. 1,252,667, which has been sanctioned but has not as yet been commenced.

The Major Works (A) are designed to irrigate, when they are fully completed and irrigation has developed, a gross area of rather more than ten million acres of crops. The cost of each project and the cost of the works for each acre irrigable by the complete project is shown in the table on the next page.

The cost per acre varies greatly, as might be expected under the very different circumstances of the various works; the figures given as the cost per acre are not, in all cases, strictly accurate, for 12 of the 35 works are constructed for navigation as well as irrigation, and it is not possible to separate from the capital account the sum expended in making the canal serve for navigation as well as for irrigation. The 35 works contain in all about 6000 miles of canals, of which about 2300 are navigable, and in addition there are some 18,000 miles of distributaries.

* Includes the actual capital cost of Kurnool Canal—a very unsuccessful work.

† Chenab Canal, Sirsa Canal, Periyar Project.

ESTIMATED COST, WHEN COMPLETED, OF MAJOR WORKS (A).—PRODUCTIVE WORKS.

Province.	Name of Works.	Maximum Discharge in cubic feet per second (as designed).	Area Irrigable by the complete project.	Full Estimated Cost of the complete project.	Cost per Acre ultimately Irrigable.
			acres.	Rs.	Rs.
Bengal	Orissa Canals	6,058	399,431	3,231,584	8·1
	Midnapore Canal	1,400	125,000	850,604	6·8
	Tidal Canal (a purely navigation work) ..	..	..	260,946	
	Sone Canals	5,955	1,016,400	2,928,830	2·8
	Total Bengal { including Tidal Canal / excluding " " " }	..	1,540,831	{7,271,964 / 7,011,018}	4·5
N.-W. Provinces ..	Ganges Canal	6,800	1,600,000	3,114,965	1·9
	Lower Ganges Canal	5,100	1,187,326	3,007,571	2·5
	Agra Canal	1,500	240,000	945,511	3·9
	Eastern Jumna Canal	2,350	370,000	307,592	0·9
	Total N.-W. Provinces		3,397,326	7,435,639	2·2
Punjab	Western Jumna Canal	2,800	550,000	1,116,642	2·0
	Bari Doab Canal	4,000	535,000	1,637,112	3·0
	Sirhind Canal (British portion)	3,840	522,000	2,441,460	4·6
	Lower Sohag and Para	1,067	93,000	76,500	0·8
	Chenab Canal *	2,350	400,000	1,037,459	2·5
	Sidhnai Canal	1,500	104,360	99,947	0·9
	Sirsa Canal	865	120,290	308,254	2·4
	Total Punjab		2,330,850	6,717,374	2·8

Madras	Godaveri	8,516	612,000	1,302,419	2·1
	Kistna I	8,126	475,000	1,490,294	3·1
	Cauvery [illegible] ystem	..	919,539	182,909	†
	Penner Anicut System	2,306	60,385	189,483	2·7
	Srivaikunthum Anicut System	1,860	30,393	147,680	4·8
	Sangam Anicut System	4,800	94,000	382,500	4·0
	Kurnool Canal	1,468	160,000	2,164,130	13·5
	Barur Tank	Reservoir	5,887	42,530	7·3
	Periyar Project	,,	101,000	503,991	5·5
	Total Madras	..	2,467,204	6,465,796	2·6
Bombay	Hathmati Canal	..	11,336	52,470	4·6
	Lower Panjhra River Works	Reservoir	12,027	46,726	3·7
	Kadwa River Works	,,	32,723	78,503	2·4
	Pravara River Works—Lakh Canal ..	..	22,760	39,546	1·7
	Matha Canal	Reservoir	55,000	629,393	11·4
	Ekruk Tank	,,	15,320	133,493	8·7
	Krishna Canal	..	25,533	75,962	2·9
	Total Bombay	..	175,299	1,056,093	6·0
Sind	Desert Canal	Not stated.	109,500	131,720	1·2
	Unharwah		18,000	35,376	2·0
	Begari Canal		104,000	168,214	1·6
	Eastern Nara Works		212,631	546,388	2·6
	Total Sind	..	444,131	881,698	2·0
	Total of all Major Works (A) (excluding the Tidal Canal)	..	10,356,641	29,567,618	2·8

* This canal is to be largely extended.

† Capital nominal, a very old work.

The Mutha Canal in Bombay, too, which is the most expensive of all per irrigable acre, derives a considerable income from the supply of water for drinking purposes in Poona, and the cost per acre would be considerably modified if this circumstance were fully taken into account. The general result, however, is sufficiently accurate, and it may be said that the works of this class cost on the average about Rx. 2·8 for each acre irrigable. The cheapest of the ten large works* is the Cauvery system of canals in Madras; but the circumstances of this system are peculiar, as the irrigation of the Cauvery delta is carried out to a large extent through the agency of natural channels, and it cannot be taken as a representative case. The other nine large works—that is, works designed to irrigate about half a million acres or more—will cost on the average Rx. 2·85 per irrigable acre, which is slightly above the average of all the works. Of these nine works the most expensive is the Orissa system in Bengal, which costs Rx. 8·1 an acre, and the next is the Midnapore Canal, also in Bengal, which costs Rx. 6·8 an acre; but both of these are works on which large sums have been expended in making the canals navigable, with results which are, in some ways, very satisfactory. The great Ganges Canal, which has the largest area of all, is also the cheapest of the large works; its cost is only Rx. 1·9 per acre. The Jhelum Canal is estimated to cost Rx. 2·95 per irrigable acre.

It has been explained that the Major Works (A) are works which are expected to be remunerative. That is, they are expected to give a net revenue greater than the interest paid by Government on the money borrowed for their construction. Taken collectively they fulfil this condition; although individual works, and even the groups of works in two of the six provinces fail to do so. Regular accounts have been compiled from the commencement, which have been annually credited with the net revenue and debited with the interest charges. Th aggregate results are shown in the table on the next page, from whi it will be seen that up to the present time only 12 of the 35 works hav worked at a profit of more than 4 per cent., but that the profits from these have been sufficient to cover the deficiencies on the other 23. The net result is that the works of this class have covered the interest charges with a gross excess to the credit of Government of nearly 4 millions of Rx., and the profit is increasing largely every year. Although there are 12 works which have proved remunerative up to the present, the profits which have been derived up to this time are almost

* Orissa, Sone, Ganges, Lower Ganges, Bari Doab, Western Jumna, Sirhind, Godaveri, Kistna, and Cauvery Canals.

MAJOR WORKS (A).—PRODUCTIVE WORKS.

Province.	Number of Works which have not paid.	Number of Works which have paid.	Total gain or loss from the commencement to date.
			Rs.
Bengal	4	0	3,690,433 loss
N.-W. Provinces	3	1	1,040,691 gain
Punjab	4	3	2,325,989 gain
Madras	4	5	4,511,120 gain
Bombay	7	0	583,110 loss
Sind	1	3	171,548 gain
Total	23	12	3,775,805 gain

entirely due to four works which have given very large returns: these are the Eastern Jumna, the Western Jumna, the Godaveri, and the Cauvery Canals; the surplus revenue of these four works amounts to more than 8½ millions of Rx.; they are all works which existed in a more or less crude and undeveloped form before they were taken up by the British Government, and which had been initiated by the Native Governments which preceded the British rule.

The modern works which have been constructed by the British Government during the last 20 years, have, up to the present, been rather a drain than a support to the irrigation revenue, and the net return on the gross capital invested in them has been below 4 per cent. But the corner is now turned; some of the new works are doing remarkably well and nearly all are improving. The latest statistics of the revenue are given in the following table, which shows that, taking all the 35 works together, the net revenue gives a return of 4·3 per cent. on the gross capital outlay of twenty-seven millions of Rx., while the works in the N.W. Provinces, the Punjab, Madras, and Sind pay 5·1, 5·9, 7·0, and 7·2 per cent. respectively on their capital.

It is not probable that the Major Works (A) in Bengal and Bombay generally, and the Kurnool Canal in Madras, which had to be purchased from a company in 1882, will ever pay 4 per cent. on the capital invested in them.

The policy of constructing irrigation works from borrowed funds was initiated in 1869. At that time about 6 millions of Rx. had been

MAJOR WORKS (A).—PRODUCTIVE WORKS.

WORKS FOR WHICH THE CAPITAL HAS BEEN BORROWED. STATEMENT OF FINANCIAL RESULTS.

Province.	Year when Revenue was first collected.	Name of the Work.	In the Year 1890-91.				
			Capital Outlay (direct and indirect) at end of the Year.	Gross Revenue of the Year.	Working Expenses, including Indirect Charges.	Net Revenue.	Percentage of Net Revenue on Capital.
			Rs.	Rs.	Rs.	Rs.	
Bengal	1869	Orissa Canals	2,476,408	34,494	46,760	**– 12,266**	loss
	1869	Midnapore Canal	842,837	23,699	20,886	2,813	0·33
	1869	Tidal Canal (navigation only)	204,739	2,804	5,357	**– 2,553**	loss
	1875	Sone Canals	2,643,335	72,917	70,210	2,707	0·10
		Total Bengal	6,167,319	133,914	143,213	**– 9,299**	loss
N.-W. Provinces	1855	Ganges Canal	2,855,614	315,225	111,439	203,786	7·1
	1879	Lower Ganges Canal	3,329,981	161,293	94,750	66,543	2·0
	1874	Agra Canal	916,234	61,238	24,720	36,518	4·0
	1830	Eastern Jumna Canal	338,672	106,412	31,895	74,517	22·0
		Total N.-W. Provinces ..	7,440,501	644,168	262,804	381,364	5·1
Punjab	1821	Western Jumna Canal	1,119,282	162,051	58,685	103,366	9·23
	1859	Bari Doab Canal	1,643,356	193,319	60,542	132,777	8·07
	1883	Sirhind Canal	2,328,739	168,426	62,075	106,351	4·05
	1884	Lower Sohag and Para	69,156	6,391	8,012	**– 1,621**	loss
	1887	Chenab Canal	570,316	9,785	9,302	483	0·08
	1886	Sidhnai Canal	93,576	18,024	7,842	10,182	10·88
	..	Sirsa Canal	62,412				
		Total Punjab	5,886,837	557,996	206,458	351,538	5·99

Madras	1846	Godaveri Delta System	1,273,203	240,009	82,680‡	157,419	12·3
	1855	Kistna Delta System	1,001,052	188,360	56,697‡	131,663	13·15
	1836	Cauvery Delta System	177,945*	311,382	245,228‡	66,154	37·1
	1860	Penner Anicut System	187,540	25,935	15,294‡	10,641	5·7
	1870	Srivaikunthum Anicut System	145,154	13,640	10,988‡	2,652	1·8
	1884	Sangam Anicut System	364,001	27,655	20,036‡	7,619	2·0
	1882†	Kurnool Canal	2,164,131	11,926	15,694‡	– 3.768	loss
	1887	Bartur Tank	41,133	740	681‡	59	0·1
	..	Periyar Project	273,168				
		Total Madras	5,627,327	819,737	447,298	372,439	7·0
Bombay	1873	Hathmati Canal	51,829	737	666	71	0·14
	1866	Lower Panjhra River Works	45,607	1,514	888	626	1·37
	1868	Kadva River Works	71,895	964	654	310	0·43
	1869	Pravara River Works—Lakh Canal ..	37,196	125	360	– 235	loss
	1873	Mutha Canal	630,713	21,758	7,983	13,775	2·19
	1872	Ekruk Tank	133,341	2,482	1,382	1,100	0·82
	1869	Krishna Canal	84,031	3,077	1,328	1,749	2·08
		Total Bombay	1,054,612	30,657	13,261	17,396	1·64
Sind	1853	Desert Canal	125,752	17,075	5,255	11,820	9·4
	1885	Unharwah	33,913	4,573	1,605	2,968	8·7
	1855	Begari Canal	167,308	23,843	8,324	15,519	9·3
	1854	Eastern Nara Works	531,902	45,579	14,215	31,364	5·9
		Total Sind	858,875	91,070	29,399	61,671	7·2
		Total of all Major Works (A)	27,035,471	2,277,542	1,102,433	1,175,109	4·3

* Capital nominal. A very old work improved by Government since 1836.

† The date on which Government purchased this canal from the company which made it.

‡ These figures are not the true working expenses of the Madras canals, but they include the adjustments due to "old irrigation," in order that the net revenue which is really due to the capital expended by Government may be shown in the next column.

expended on the 14 Major Works (A) which were at that time in operation:* since then some 3½ millions more have been spent upon them. These 14 works paid in 1891 about 10 per cent. on their capital cost. From 1869–78 was the period of greatest activity in the construction of irrigation works; during that time about 11 millions of Rx. were expended. During this decade 11 works† came into operation. The expenditure of the decade was mainly on these, but partly on the older 14 works just mentioned, and also on two of those (Sirhind and Lower Ganges) which came into operation at a later time. From 1879 to 1888 the expenditure gradually decreased. About 7 millions of Rx. were spent during the ten years on construction of works, and 2 millions more on the purchase of the Kurnool Canal. The 11 works which were opened in 1869–78 are chiefly the works in Bengal and Bombay; the revenue from these, taken collectively, did little more than cover their working expenses in 1891, and it is very doubtful whether more than one or two of them will ever prove financially successful, although there is much to be said from other points of view in their favour. The eight works‡ opened in 1879–88 (including the Kurnool Canal, which was purchased in that period, although it had been in operation before that) worked in 1891 at a small profit, and there is every reason to think that all of them (except the Kurnool Canal which is an absolutely hopeless enterprise) will ultimately prove financially successful. Indeed the Sirhind and the Sidhnai Canals are now paying over 4 per cent., and the Lower Ganges is improving steadily.

Among the six provinces in which the works of this class lie, Madras and Sind stand prominently forward as those in which all the works which have been in operation for more than ten years are thoroughly successful. In the North-West Provinces all the four works (which now pay collectively more than 5 per cent.) will be thoroughly successful, and in the Punjab the two older works (Bari

* North-Western Provinces: Ganges, Eastern Jumna.
Punjab: Bari Doab, Western Jumna.
Madras: Godaveri, Kistna, Cauvery, Penner.
Bombay: Lower Panjhra, Kadva River.
Sind: Desert, Unharwah, Begari, Eastern Nara.

† Bengal: Orissa, Midnapore, Tidal, Sone.
North-Western Provinces: Agra.
Madras: Srivaikunthum.
Bombay: Hathmati, Pravara River, Mutha, Ekruk Tank, Krishna.

‡ North-Western Provinces: Lower Ganges.
Punjab: Sirhind, Lower Sohag and Para, Sidhnai, Chenab.
Madras: Sungam, Kurnool, Barur.

Doab and Western Jumna) pay well, and the four younger works are making rapid strides. One of these, the Sidhnai Canal, is a very remarkable, if not an unprecedented, case, as it paid nearly 14 per cent. on its capital during the second year it was in operation, and gave over 10 per cent in 1891. The Sirhind Canal, too, has irrigated far larger areas than were expected from it at the present stage of its career. Of the Bengal works little hope can be entertained; the normal rainfall there is too large and too regular to make irrigation an urgent requirement for agricultural prosperity, these works must be looked on as a protection against occasional drought and famine rather than a possible source of financial profit to the Government.

MAJOR WORKS (B).—PROTECTIVE WORKS.

The five works of this class are entirely of modern origin: the amount expended on them and the financial results of 1890-91 are shown in the following statement:—

Province.	Year in which revenue was first collected.	Name of work.	Capital outlay (direct and indirect) at end of the year.	Gross revenue.	Working expenses.	Net revenue.	Area irrigable by the complete project.	Cost of the complete project per acre.
			Rs.	Rs.	Rs.	Rs.	Acres.	Rs.
N.-W. Provinces	1885	Betwa Canal ..	417,815	7,448	11,486	−4,038	150,000	2·9
Punjab ..	1885	Swat River Canal	360,349	25,048	10,909	14,139	120,000	3·1
Madras ..	..	Rushikulya Project	207,319	..	..	..	120,000	3·6
Bombay ..	1885	Nira Canal	500,244	3,608	3,048	560	227,500	2·3
„	1884	Mhaswad Tank ..	203,477	1,943	1,272	670	106,214	2·0
		Total	1,689,204	38,047	26,715	11,331	723,720	2·3

In addition to these there are two works in abeyance in Bombay on which Rs. 10,179 have been spent. The works are all approaching completion; they comprise about 400 miles of canal and 800 miles of distributary channels.

As the works are not expected to pay 4 per cent on their capital cost, and as the earliest of them was only opened for irrigation in 1884, it is not surprising that the net revenue is so small. But the results are improving and will continue to do so. The Swat River Canal, which is

in several respects rather a remarkable work, has shown the same rapid development of irrigation which has characterised other works in the Punjab: it has irrigated far larger areas than were anticipated, and it has already proved to be a remunerative work. It was primarily undertaken, chiefly on political grounds, in order to settle the lawless tribes residing in the north-east corner of the Peshawur valley where the canal lies.

Minor Works (A).

The 77 works of this class which are in operation are of a more varied character than the Major Works; they comprise perennial canals, inundation canals, navigation canals, reservoirs, tanks, embankments, a workshop, and one work for the supply of drinking water. About one-fourth of the works were originated by Native Rulers, the predecessors of the British in the government of the country, and have been taken up and improved by the British Government. In some cases the capital account is rather questionable, as the value of the old native works has not been included. The statement on next page shows the number and cost of the works by provinces, and the financial results obtained in the last year of which the statistics are available.

The works which are in operation in this class comprise about 6463 miles of canals and 2600 miles of distributaries as shown below. These works are all practically completed; only a very few miles of channels remain to be constructed.

Province.	Canals.	Distributaries.
	miles.	miles.
Baluchistan	5	40
Rajputana	..	..
Lower Burma	..	..
Bengal	829	..
N.-W. Provinces	20	545
Punjab	2608	591
Madras	1173	931
Bombay	1828	493
Sind		
Total	6463	2600

MINOR WORKS (A).—WORKS OF WHICH CAPITAL AND REVENUE ACCOUNTS ARE KEPT.

Province.	Number of Works.	Class of Works.	Capital Expenditure including Indirect Charges.	Gross Revenue.	Working Expenses excluding Indirect Charges.	Net Revenue.	Percentage on Capital Outlay.	Approximate Area Irrigable by Complete Projects.
			In the Year 1890-91.					
			Rs.	Rs.	Rs.	Rs.		acres.
Baluchistan ..	4	One reservoir; three irrigation canals	158,083	1,621	2,137	– 516	loss	35,000
Rajputana ..	3	Three groups of tanks ..	166,790	12,475	5,814	6,661	4·0	50,000
Burma (Lower)	3	Embankments	314,209	70,176	19,932	50,244	16·0	
Bengal	3	One irrigation canal; two navigation * systems ..	1,932,872	62,766	42,079	20,687	2·0	50,000
N.-W. Provinces	4	Irrigation canals	249,310	25,671	16,477	9,194	3·7	240,000
Punjab	5	Four sets of inundation canals and a workshop ..	187,668	102,358	82,530	19,828	10·5	840,000
Madras	21	Four navigable † canals; a water supply system; a large tank ‡; and a number of irrigation systems	1,405,533	73,792	42,717	31,075	2·2	370,000
Bombay	27	Mostly tanks	662,865	9,873	6,113	3,760	0·5	175,000
Sind	7	Inundation canals	335,054	134,322	54,234	80,088	23·8	600,000
	77	Total Minor Works (A) ..	4,512,384	493,054	272,033	221,021	4·8	2,360,000

* The Calcutta and Eastern Canals. The Orissa Coast Canal.
† The Buckingham Canal. Chilka Lake Canal. Venardiem Canal. Ganjam-Gopalpur Canal.
‡ The Chembrambaukham Tank.

The area irrigable by this class of works is approximately 2,360,000 acres, as shown in round figures in the above statement. Three of the works, the Calcutta and Eastern Canals, the Orissa Coast Canal, and the Buckingham Canal, are extensive systems of navigation on the east coast, they comprise about 1050 miles of navigable channels: of these three the first alone is worked at a profit, it is an old work, while the other two have been constructed quite recently and are not yet fully completed.

The works in this class, taken collectively, are more remunerative than the Major Works (A). It will be seen that the Minor Works (A) owe their success mainly to the Irrawaddy embankments in Burma, and to the inundation canals of Sind and the Punjab: although there are other works, such as the tanks in Rajputana and one of the Bengal navigation canals, which give more than 4 per cent. The numerous small works in Bombay are unremunerative, and there is but little hope that the returns derived from them will materially improve. The works in this class, which were taken over by the British Government in a more or less developed condition, were chiefly the inundation canals of the Punjab and Sind and the Rajputana tanks: the remunerative results of this class of works, as a whole, is no doubt partly due to the fact that the capital account does not take cognisance of the value of the works when they were acquired. But, on the other hand, it must not be forgotten that the works have been extended, altered, and improved by the British Government, and that, in some cases—as on the river Indus in the Punjab and Sind—lines of embankment are maintained at the expense of the canals, which do not only protect the irrigated areas, but which are often of considerable value for other purposes quite unconnected with the sources from which the revenue credited to the canals is realised.

Minor Works (B).

The Minor Works (B), although generally works of little importance from an engineering point of view, are of considerable value both to the agricultural and financial interests of the country. There is no capital account of any of them, and the cost of the great majority is quite unknown, as they existed long before they were taken in hand by the British Government. The works in Bengal consist of two new canals, partly for irrigation and partly for water-supply purposes, which are not financially remunerative, and one system of navigation, through river channels conserved for the purpose, which has a considerable net revenue. The works in the Punjab are old inundation canals. The

Madras works are almost exclusively tanks and reservoirs for irrigation: so are the works in Bombay. The works of this class in Sind are small inundation canals. The following statement shows the receipts and expenditure during 1890–91:—

MINOR WORKS (B). WORKS OF WHICH CAPITAL ACCOUNTS ARE NOT KEPT.

Province.	Gross Revenue.	Expenditure.	Net Receipts.
	Rs.	Rs.	Rs.
Bengal	20,407	14,468	5,939
N.-W. Provinces ..	21,816	9,823	11,993
Punjab	39,560	20,158	19,402
Madras	636,498	230,013	406,485
Bombay	52,736	19,625	33,111
Sind	303,315	200,522	102,793
Total	974,332	394,609	579,723

The revenue derived from these small irrigation systems is mainly a share of the Land Revenue which is held to be due to the irrigation effected. In the accounts of the Empire this revenue is not shown to the credit of the works, but to the credit of Land Revenue, so that the results shown in the above statement are not apparent in those accounts. The share of Land Revenue which is assessed as due to the works is rather empirically determined, and the accuracy of it may be questioned; were the revenue, however, really much smaller that it is stated to be, the net result must be a large profit to the State.

The statement on next page shows the areas irrigated by the four classes of irrigation works in India in 1890-91.

The gross area irrigated in the year by the four classes of works was 13,405,195 acres, or nearly 21,000 square miles. The area irrigated by the first three classes of works—those of which capital and revenue accounts are kept, and of which the statistics are most reliable—was about 60 per cent. of the area which can be irrigated by the complete projects when irrigation has fully developed, and, although there will certainly be failures, in some cases, to attain to the full area irrigable, it is known that, in others, there will be an ultimate area in excess of the forecast. So that it is not improbable that ultimately the area irrigated by the Major Works (A) and (B) and the Minor Works (A), that is all

the works of which capital accounts are kept, will approximate to 12 million acres."

AREAS IRRIGATED BY ALL FOUR CLASSES OF WORKS.

Provinces.	Works of which Capital and Revenue Accounts are kept.					Works of which no Capital Accounts are kept.		
	Major Works.		Minor Works.	Average rate of Working Expenses per acre on the three foregoing classes.	Average rate charged per acre irrigated.	Minor Works.	Ratio per cent. of Expenditure to Gross Revenue per acre.	
	A.	B.	A.			B.		
	acres.	acres.	acres.	rupees.	rupees.	acres.	rupees.	rupees.
Baluchistan ..	..	..	..	..	..	..	..	..
Rajputana	..	..	..	..	..	..	..	..
Burma	..	..	..	..	..	..	..	..
Bengal	543,315	..	2,226	2·60	1·81	..	..	..
N.-W. Provinces	1,853,824	33,953	126,337	1·48	3·3	63,761	..	..
Punjab	1,737,231	88,875	723,674	1·18	2·50	292,878	0·68	0·88
Madras	2,346,732	..	421,043	0·83	3·3	2,746,409	..	..
Bombay	26,565	24,019	25,317	3·15	4·19	145,563	1·35	5·40
Sind	547,954	..	772,863	0·66	2·24	912,656	1·10	2·41
Total irrigated in 1890-91	7,025,621	146,847	2,071,460	..	..	4,161,267	..	..
Total area irrigable by the works when they are complete	10,356,641	723,720	2,360,000					

The rates which are charged for the use of water for purposes of irrigation vary largely in different parts of India and for different crops. In some cases a charge is made for a single watering, and in others a special rate is imposed for water taken during certain months, but generally the charge is an acreage rate for irrigating the crop to maturity. Excluding very exceptional cases, it may be said that this rate varies from 1 rupee an acre for rice crops in some parts of Bengal and Sind up to 20 rupees * an acre, which is not an extreme rate in Bombay for sugar-cane crops. The average rates in the different provinces, including enhanced land revenue and all similar charges made on account of the water supplied, are shown in the statement in the preceding paragraph. The average rate for the whole of India is rather more than 2·8 rupees an acre.

* A rate of 50 rupees per acre has actually been realised in the immediate neighbourhood of Poona.

Statements showing the value of all crops irrigated by the Major Works (A) and (B) and the Minor Works (A) are prepared in all provinces except Sind. The following statement has been prepared for the year 1890–91 :—

VALUE OF IRRIGATED CROPS.

Province.	Major Works (A).		Major Works (B).		Minor Works (A).		All three classes.		
	Gross value of crops irrigated.	Average value per acre.	Gross value of crops irrigated.	Average value per acre.	Gross value of crops irrigated.	Average value per acre.	Average value of crops per acre.	Average rate charged for each acre irrigated.	Percentage of rate on value of all crops.
	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.	Rupees.	
Bengal ..	16,604,844	30·5	..	..	49,567	22·4	30·5	1·81	6·0
N.-W. Provinces	65,825,569	35·4	1,204,297	35·4	4,987,823	39·5	35·7	3·3	9·2
Punjab ..	59,910,070	34·5	2,475,179	27·8	18,228,285	25·2	31·6	2·50	7·9
Madras ..	56,373,845	24·7	..	..	8,339,618	20·8	24·2	3·3	13·6
Bombay ..	2,436,480	91·9	535,461	22·3	1,025,754	42·7	53·4	4·19	7·8
Sind (not available) ..	..	..	..	..	..	..	..	..	..

The percentage which the rate charged for the water bears to the value of the crops is, theoretically, a gauge of the severity of the charge on the cultivator. Gauged by this standard the Bombay rates, which appear to be extremely high, are shown to be moderate, and this is really the fact when the very high value of the sugar-cane crop in that province is taken into account. The rates in Bombay have lately been raised throughout the province. The Punjab rates, which are only 7·9 per cent. on the value of the crops, are known to be capable of enhancement without hardship. The Madras rates are far the highest of all with reference to the value of the crops ; this is partly due to the very low average value of the crops in Madras in consequence of the almost exclusive cultivation of rice by irrigation from the canals, but it is also due to no small extent to good administration and efficient technical management. The very low rates charged in Bengal are partly due to the fact that irrigation in that province is not as much required as elsewhere ; partly—indeed in no small degree—to excessive concessions to agitation, and partly to the fact that the system of land settlement in that province is such that the landlords absorb a portion of the profits which in other provinces are realised by Government and credited to the revenue accounts.

The chief crops which are watered by the canals are sugar-cane, wheat, rice, cotton, and indigo. Madras and Bengal are the chief rice-growing provinces, 93·5 and 82·2 per cent. of the area of the irrigated crops being rice. In the North-Western Provinces and the Punjab, wheat is the staple, more than one-third of the irrigated area being under that crop. In Bombay irrigation is chiefly given to sugar-cane and wheat, but the areas are small. In Sind the irrigated area is mainly jowari and rice. The following statement, which was compiled a few years ago, shows the statistics of the five chief crops:—

Province.	Value of Crops per acre.					Percentage of acreage of Crops mentioned to total acreage irrigated of all Crops.					Percentage of value of Crops mentioned to the total value of all Crops irrigated.				
	Sugar-cane.	Wheat.	Rice.	Cotton.	Indigo.	Sugar-cane.	Wheat.	Rice.	Cotton.	Indigo.	Sugar-cane.	Wheat.	Rice.	Cotton.	Indigo.
	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.
Bengal	53·3	16·4	17·1	16·0	42·6	5·2	4·5	82·2	0·04	0·06	14·7	4·2	73·6	0·03	0·1
North-west Provinces ..	66·0	40·9	27·6	30·0	20·0	13·2	34·0	6·8	3·2	14·2	25·0	40·0	5·4	2·8	8·1
Punjab	100·0	32·0	37·3	32·1	45·0	3·7	34·8	7·0	10·0	3·9	12·2	36·7	8·6	10·4	5·7
Madras	*	*	20·0	*	*	*	*	93·5	*	*	*	*	92·4	*	*
Bombay ..	283·1	23·8	36·6	..	..	15·2	19·7	12·5	..	..	68·2	7·4	7·3	..	..
Sind (not available)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

* Not given—very small, if any.

The average value of an acre of irrigated crop in the five provinces is about 30 rupees. The gross value, at this rate, of the entire area of 13,405,195 acres which was irrigated in 1890–91 by all the four classes of works which are administered by the Government, was 400 millions of rupees (say 25 million pounds sterling). Taking all the circumstances of the different provinces into account, it may be said that, at a moderate computation, one-third to one-half of this sum represents the value of the increased out-turn from the fields due to irrigation.

This figure displays, perhaps more forcibly than any other, the magnitude of the agricultural interests which are bound up with the irrigation works of India. The extent to which the perfection of the irrigated crops is dependent on irrigation varies greatly with the climatic conditions of the different provinces, and in all provinces according to the incidence of the rainfall during any particular season. In Sind and in some parts of the Punjab, where the rainfall averages about 3 or 4 inches, or even less, in the year, the crops are at all times dependent

on the canals; they could not be grown at all unless water wa... for irrigation. In Bengal, on the other hand, where the rainfa... from about 40 to 50 inches, and is usually well distributed ... reference to the necessities of the crops, the rice crops (82 per cent. ... the whole area) can, in all ordinary years, be matured without irrigation at all, although, even in ordinary years, it has been proved that the irrigated crops give a better out-turn than unirrigated ones by about 20 per cent. In Bombay also the conditions are somewhat similar. In these provinces the value of the irrigation works becomes apparent only in the years of famine and drought. In such years it occasionally happens—as indeed it did happen in the kharcef season of 1888 on the Sone Canal in Bengal—that the crop withers almost entirely when irrigation cannot reach it. At such times an irrigation work which has cost, say, the average figure of 28 rupees an acre, and which can ensure crops worth, say, 30 rupees an acre, finds, in the eyes of the cultivators at any rate, ample excuse for its construction, even although, as is unfortunately the case with all the irrigation works of Bengal and Bombay, the financial results are unsatisfactory when viewed in the light of the Government accounts.

It has not infrequently been assumed that the probabilities of the success of a new irrigation project can be gauged by a consideration of the incidence of the rainfall on the tract commanded. The rainfall is no doubt one of the chief factors to be considered; but the statistics show conclusively that there must be other factors of at least equal, if not of greater, weight, which must be taken into account in estimating the success or failure of an irrigation system. For example, the annual ...infall in that portion of Bombay where the irrigation works lie is ...ty, while that in Madras is copious, but in the former case the ...on work... ...remunerative, whereas in Madras they are, with ...tive. Even a more striking instance can be ...uvery Canals, which irrigate a larger area ...n capital than any other irrigation ...ere the average rainfall is about ... Kurnool Canal, which is the most ... works in India, lies within 300 miles ...nce, in a tract where the average rainfall ... this case the difference in the nature of the ...or the difference in the results; but the causes which ...iking differences are but little ...derstood, and ...d but slight clue to them ...

...n Madras the temperature is generally so equable that it is ... to grow two and even three crops of rice on the same field ...g the year: this is not possible in the more variable climates. It ...ay be that this climatic difference explains the great discrepancy in the results obtained in Madras and in the neighbouring province of Bengal where no profits are realised. It should also be noted that the actual amount of the rainfall is of less importance than its distribution. Differences in soil and in methods of cultivation have also great weight in determining the success of an irrigation project, and it is by no means improbable that the different systems of land tenure which are in force in different parts of India have a powerful influence in this matter. There is little doubt that the ryotwari system of the Punjab lends itself much more readily to the system of irrigation from large canals than the more obstructive zemindari system of Bengal. Whatever the causes may be which should determine the results obtained, it must be admitted that much ignorance has prevailed concerning them, and this has led to the construction of some works which have signally failed to produce the results which were anticipated by their projectors.

The Indian Famine Commission, which reported in 1880 on the measures of protection and prevention to be adopted in anticipation of future famines, writes as follows* :—"Among the means that may be adopted for giving India direct protection from famine arising from drought, the first place must unquestionably be assigned to works of irrigation. It has been too much the custom, in discussions as to the policy of constructing such works, to measure their value by their financial success considered only with reference to the net return ... Government on the capital invested in them. Th... ...ue value of ... gation works is to be judged very differently. ... ... the direct protection afforded by them in ... saving of human life, by the avoidance ... of the outlay incurred in costly mea... years of drought that they are o... they are of great service and a gre... to all agricultural operations, increa... crops, and enabling more valuable de... From the Punjab in the north to Tinneve... tremity of the peninsula, wherever irrigation is prac... manifest; and ...e may see rice, sugar-cane, or ...

* Part II. section ii. page 15...

place of millet or barley, and broad stretches of indigo grown at a season when unwatered lands must lie absolutely unproductive."

More recent experience has emphasised the truth of this remark. There are many instances in the Sone canals in Bengal in which the higher lands, which used to lie waste, or which produced very poor cold-weather crops, have been converted into flourishing rice-fields.

The area irrigated in India by the first three classes of works has increased from 7 million to 10 million acres in the last thirteen years, on the basis of the figures of 1877–78 and 1890–91; these are:—

COMPARISON OF AREAS IRRIGATED.

Province.	Area irrigated in 1877-78.	Area irrigated in 1890-91.	
	Acres.	Acres.	
Bengal	454,000	545,541	These figures do not include the areas irrigated by Minor Works (B).
N.-W. Provinces	1,461,000	2,014,114	
Punjab	1,324,000	2,549,780	
Madras	2,100,000	2,767,775	
Bombay	25,000	75,901	
Sind	1,800,000	2,203,473	Includes irrigation by Minor Works (B).
Total	7,164,000	10,156,584	

The increase in thirteen years has been about 40 per cent.

It is not easy to measure with accuracy the degree of protection against famine which is afforded by the irrigation works to the various provinces in which they lie, but the statistics which have been collected afford some clue to this. The Famine Commission* discussed this question in some detail: it was estimated that each acre of irrigated food-grains would feed from 2·5 to 3·0 persons for one year according to the nature of the crops grown. In the following table the figure of 2·5 persons per acre has been taken, and the area of food-grains which the works could mature has been calculated on the assumption that, in a famine year, the gross area irrigable by the canals would be irrigated,

* Part II., pages 71-75.

and that the proportion of food-crops grown would be the same as obtains now on the areas irrigated. This assumption is, perhaps, rather unfavourable to the irrigation works, as, in a famine year, it is probable that the cultivation would be mainly confined to food-crops, and that dyes, drugs, oil-seeds, and other non-edible crops would not be cultivated. The statement takes cognisance of the works classed as Major Works (A) and (B) and Minor Works (A) only, and omits Minor Works (B) entirely; this is done because the Minor Works (B) consist largely of tanks, which might probably fail to a considerable extent in a famine year:—

PROTECTION AGAINST FAMINE.

Province.	Approximate gross area ultimately irrigable by Major Works (A) and (B) and Minor Works (A).	Approximate percentage of food-grains to actual Irrigated area.	Area of food-grains ensured by the canals.	Population for which the Irrigation Works could supply food for one year.	Total population of the Provinces.	Percentage of the population which would be fed for one year by the Irrigation Works alone.
	Acres.		Acres.	No.	No.	
Bengal	1,576,000	93	1,466,000	3,665,000	71,000,000	5·2
North-west Provinces ..	3,787,000	65	2,462,000	6,155,000	47,000,000	13·0
Punjab	3,291,000	67	2,205,000	5,514,000	21,000,000	26·2
Madras	2,957,000	95	2,809,000	7,022,000	35,000,000	20·0
Bombay ..	684,000	70	479,000	1,198,000	19,000,000	17·5
Sind	1,044,000	82	856,000	2,140,000		
Total	13,334,000	..	10,277,000	25,692,000	193,000,000	13·3

This statement shows that, generally speaking, the food of about one-eighth of the entire population is ensured by the irrigation works. But actually the measure of protection afforded is much larger, for there are many portions of the provinces included in the above statement which are naturally protected from any fear of famine. In Bengal, for instance, where the proportion of the population shown as protected is only 5·2 per cent., there is a large area, lying generally to the east of a line drawn north and south through Calcutta, which is practically free from all risk of famine. The portions in Bengal which are most liable to famine are Behar and Orissa: the Sone and Orissa irrigation works in those districts afford a sufficient measure of protection to the population. The same remarks apply in a smaller degree to all

provinces: it must also be remembered that a famine never strikes the whole area of a province simultaneously, and that even in the area afflicted with drought it is always possible to raise a certain area of food-grains by irrigation from wells, tanks, and streams. The statement does not include the smaller provinces of British India, containing some twenty-four millions of people, nor the Independent Native States with about sixty-four millions: in some of these the protection against famine is naturally good, and in others there are some efficient irrigation works of small magnitude, but the greater proportion of the population in these parts must rely entirely upon importation as a protection against famine.

The experience which has been gained during the last thirty years, no less by the failures than by the successes which have been recorded, will enable the Government to proceed with more security with the prosecution of new works and with the extension of the old systems. One of the provinces which, perhaps more than any other, needs a liberal expenditure on works of irrigation, is Sind. The works which do exist are very remunerative financially, and very productive from an agricultural point of view; and yet, although the province has been loudly calling for money for years, the progress made has been small, because the demands have been sparingly and insufficiently met, and no encouragement has been given to the preparation of new projects. Only a small portion of the waters of the Indus are utilised, and not only are improvements in the existing works most desirable, but projects ought to be matured for new ones, not only in Sind, but in the higher courses of the river.

The Indus has many features in common with the Nile, and the country bordering it is nearly as rainless as Egypt. It seems to be a matter worthy of consideration whether the basin system of Egypt might not, in some cases at any rate, be effectively introduced in the tracts commanded by the river. The question of the construction of large perennial canals from the Indus has been mooted more than once, but has from time to time been set aside; there is no question that such canals might be constructed, and would, probably, be as successful as are the perennial canals of Egypt.

During the last ten years more progress has been made in the Punjab in the prosecution of new works than in any other province, and the results have been most encouraging. It has been already shown (page 276) that the Punjab Irrigation Works pay 6 per cent.

A project for the extension of the Chenab Canal has been sanctioned,

at a cost exceeding one and a half millions of Rx., and is now in hand; this will add 700,000 acres to the irrigation of the province.

The project for the Jhelum Canal, in the Punjab, which is a most promising one, was sanctioned four years ago, but is not commenced yet, mainly because the Government has not been in a position to find the necessary funds. This project, which will irrigate 423,360 acres of land, is estimated to cost Rx. 1,252,667, and to pay over 8 per cent. on the capital outlay. This and other projects in the Punjab should be pushed on as soon as possible: the field is large and promising. In the North-West Provinces, where a return of more than 5 per cent. on the capital outlay is now earned, a magnificent project, called the Sarda Canal, has long lain dormant. This project is sketched in Plate IX., page 18, in dotted lines. The agricultural advantages of it are acknowledged, and its financial success is considered to be established; but the work does not proceed. The original project contemplated the irrigation of some 2,380,000 acres of land at a cost of Rx. 6,170,000; and there is a smaller project for 600,000 acres at a cost of Rx. 2,150,000. The project was fully prepared in 1870, but its progress was then interrupted by the opposition of some of the principal landowners. Now it is delayed chiefly because the Imperial and Provincial Governments have not been able to come to terms as to which of them should bear the financial responsibility of the project. A man might as well hesitate to draw his dividends because he could not decide whether he should place them in his left-hand pocket or in the right-hand one. In 1880 the Famine Commission reported with reference to this project that "a return of 5 per cent, may be anticipated: we think that the scheme ought not to be any longer rejected unless grave and substantial objections to it can be established." There are two other projects in this province—the Dassan Canal and the Ken Canal—which [illegible] some advantages, but must give place to the Sarda project.

In Madras the best sites for large works in the deltas of the three great rivers have already been taken up with excellent results. The conformation of the land in the higher parts of the province is not favourable to extensive projects, such as those of Upper India, and the supply in the streams is largely dependent on local rainfall. The extension of irrigation works will probably be confined to the construction of storage works in the hills. In Bengal there is no prospect of the successful prosecution of new works, nor are they required. In Bombay there is little prospect of financial success, but an extension of reservoir

projects may be required as a protection against famine. A new field has been opened up by the annexation of Upper Burma: there is reason to think that irrigation works in that province may not only be remunerative, but will form a valuable aid to the final pacification of the country.

The gross capital expenditure which has been incurred by the British Government on the irrigation works of India is slightly more than thirty-three millions of Rx. Thus:—

	Rx.
Major Works (A)	27,035,471
,, ,, (B)	1,689,204
Minor Works (A)	4,512,384
Total ..	33,237,059

The works on which this expenditure has been incurred yield at present a net return of Rx. 1,407,461, which is 4·2 per cent. on the outlay, and there is no doubt that this return will improve. In addition to this revenue, the Minor Works (B), on which no capital has been expended by the British Government, gave a net return of Rx. 579,723 in 1890-91, so that, if the irrigation works of India which are under the administration of Government are regarded as a whole, they give an aggregate net return into the Treasury of nearly two millions of Rx. a year. This sum represents the actual annual profit which the Government of India derives from this property, although it must be admitted that the greater portion of this profit is due to the works initiated by the natives of India before the British occupation of the country, which have been improved and developed by English engineers. Viewed from the point of view of the Government Treasury, there can then be no doubt of the advantage derived from the irrigation works. The landowners derive a benefit from the works by the increased rentals which they obtain,* while the cultivators of the fields have at least equal reason to be satisfied with the result, for the out-turn of their fields is not only ensured in years of drought, but the amount of produce is very

* The Famine Commission reported in 1880, para. 9, page 151, that "the ordinary rental of land in Northern India is doubled by irrigation, while in eleven districts in Madras the average rental rises from Rs. 1.4.0 to Rs. 5.4.0 per acre when supplied with water. In Tinnevelly the increase is nearly tenfold. In the eight years preceding 1875-76 the average selling price of irrigated lands in the Cavari Valley of Mysore was 35/. an acre: the best 'dry' land at the same time did not fetch above 2/. or 3/. 10s." It does not of course follow that the whole of this increase in value goes to the credit of the landlord.

largely increased even in ordinary years, at a cost to them which may be roughly stated to be about 30 per cent. of the increased out-turn. In addition to the advantages which accrue to those most immediately concerned, there are the many indirect advantages which follow from the large increase in the food supply of India which the irrigation works afford, and from the absolute security which is obtained in many parts of the country where, without irrigation, the crops are, at the best, both inferior and precarious.

APPENDIX I.

CHEZY'S FORMULA FOR CALCULATING THE DISCHARGE OF OPEN CHANNELS.

Notation applicable to Appendices I., II., III., and IV. All dimensions in feet and decimals. Velocities and discharges in feet and cubic feet per second.

Q = quantity of water discharged in cubic feet per second.
V = mean velocity in feet per second.
V_s = surface velocity.
A = sectional area.
P = wetted perimeter exclusive of the surface width.
l = a longitudinal length in the direction of flow.
h = the fall in any length; also a vertical head of pressure.
W_s = a transverse width at water surface.
$R = \frac{A}{P}$ = hydraulic mean depth or mean hydraulic radius.
$R_1 = \frac{A}{P + W_s}$ prime or diminished mean hydraulic radius.
$S = \frac{h}{l}$ = ratio of fall to length or hydraulic slope in terms of its sine.
c = coefficient in a formula of the Chezy type.
k = any constant.

Chezy's formula is—

$$V = c\sqrt{RS}.$$
$$Q = A \times V.$$

Various constant values of the coefficient c have been given by different authorities, Eytelwein, d'Aubisson, and others. Kutter found that c varies with the character of the bed and sides, the hydraulic mean depth and the fall. The recent experiments of Major Cunningham, R.E., show that Kutter's formula gives results which are within 7½ per cent. of those determined by the most careful observations. Bazin's formula differs from that of Kutter in making c independent of the fall and in not dividing canals in earth into different classes according to the condition of their bed and sides. It corresponds roughly with the Kutter formula, in the case of a fall of from 4 to 6 inches per mile, when N the coefficient of rugosity = 0·025.

The following constant values of c have been given by the authorities quoted, but, as stated above, the value of the coefficient has been proved to be variable, and discharges calculated by the aid of the following values are only fairly reliable in the case of large values of R :—

Eytelwein	$c = 93{\cdot}4$	d'Aubisson.. ..	$c = 95{\cdot}6$
Beardmore.. ..	$c = 94{\cdot}2$	Downing	$c = 100$

The Chezy formula may be used in the form $V = c_1 \times 100 \sqrt{RS}$ where $c_1 = \frac{c}{100}$, which is perhaps more convenient for purposes of calculation.

APPENDIX II.

BAZIN'S FORMULA FOR CALCULATING THE DISCHARGE OF OPEN CHANNELS.

Different coefficients are used according to the nature of the bed and sides of the channel.

Type 1. Very even. — Bed and sides composed of fine plaster, planed planks.

$$V = \frac{1}{\sqrt{0{\cdot}0000457\left(\frac{R + 0{\cdot}098}{R}\right)}} \sqrt{RS}$$

Type 2. Even-cut stone. — Bed and sides composed of brickwork, planking.

$$V = \frac{1}{\sqrt{0{\cdot}0000579\left(\frac{R + 0{\cdot}23}{R}\right)}} \sqrt{RS}$$

Type 3. Slightly uneven. — Bed and sides composed of rubble masonry.

$$V = \frac{1}{\sqrt{0{\cdot}00007315\left(\frac{R + 0{\cdot}82}{R}\right)}} \sqrt{RS}$$

Type 4. Uneven. — Bed and sides composed of earth, earthen channels.

$$V = \frac{1}{\sqrt{0{\cdot}00008534\left(\frac{R + 0{\cdot}41}{R}\right)}} \sqrt{RS}$$

This formula may be put into the form $Q = c\sqrt{S} \times A\sqrt{R}$, the first term of which depends on the coefficient employed and on the hydraulic gradient. It

has been used in this shape in Higham's tables. It may here be stated that Bazin's formula is not applicable in the case of rivers where the value of R is large.

Values of coefficient, Bazin's Formula, Type 4. Bed and sides composed of earth, earthen channels.

R.	c.	R.	c.	R.	c.
0·5	35·7	2·0	62·0	4·0	76·1
·6	38·4	·1	63·0	·5	78·3
·7	41·0	·2	63·9	5·0	80·2
·8	43·6	·3	64·8	·5	81·9
·9	45·9	·4	65·7	6·0	83·4
1·0	47·9	·5	66·6	·5	84·8
·1	49·7	·6	67·4	7·0	86·0
·2	51·4	·7	68·2	·5	87·0
·3	53·0	·8	68·9	8·0	88·0
·4	54·5	·9	69·6	·5	89·0
·5	55·9	3·0	70·3	9·0	90·0
·6	57·2	·2	71·6	·5	90·6
·7	58·5	·4	72·8	10·0	91·2
·8	59·8	·6	74·0	11·0	92·4
·9	60·9	·8	75·1	12·0	93·4

Relation between the Greatest Surface and Mean Velocity.

The following relation between the greatest surface and mean velocity was deduced by Bazin from the experiments on which the preceding formulæ are founded :—

$$V = V_s - 25{\cdot}4\sqrt{RS} \text{ or } V = V_s \times \frac{c}{c + 25{\cdot}4}.$$

Cunningham (cap. XX., sect. 22 *b*) states that this formula gives results which may be considerably in defect for earthen channels. It was calculated from experiments showing the relation between the mean velocity of the section and the maximum velocity, which is usually not identical with the maximum surface velocity. It is, however, accepted by Unwin (Art. 102) as at least a good approximation to the truth for channels not widely differing from those experimented on by Bazin (small earthen channels with a moderate slope).

The table below, giving numerical values for $\frac{c}{c+25\cdot4}$ in the formula, is taken from Unwin:—

Hydraulic Mean Depth R.	Type 1.	Type 2.	Type 3.	Type 4.	Very Rough Channels encumbered with Detritus.
·25	·83	·79	·69	·51	·42
·50	·84	·81	·74	·58	·50
·75	·84	·82	·76	·63	·55
1·0	·85	·82	·77	·65	·58
2·0	·85	·83	·79	·71	·64
3·0	·85	·83	·80	·73	·67
4·0	·85	·83	·81	·75	·70
5·0	·85	·83	·81	·76	·71
6·0	·85	·84	·81	·77	·72
7·0	·85	·84	·81	·78	·73
8·0	·85	·84	·81	·78	·73
9·0	·85	·84	·82	·78	·74
10·0	·85	·84	·82	·78	·74

APPENDIX III.

KUTTER'S FORMULA FOR CALCULATING THE DISCHARGE OF OPEN CHANNELS.

$$V = \frac{1\cdot811 + N\left(41\cdot6 + \frac{0\cdot00281}{S}\right)}{\sqrt{R} + N\left(41\cdot6 + \frac{0\cdot00281}{S}\right)} \frac{R}{N}\sqrt{S}$$

In this formula N is a coefficient dependent on the nature of the bed and sides of the channel.

The following are the values of N for different materials given by Jackson:*—

1. Well planed planks .. .. 0·009
2. Plaster in pure cement (enamelled pipes) .. .. .. 0·010
3. Plaster in cement, one-third sand .. .. 0·011

* See Jackson, Canal and Culvert Tables.

4. Unplaned timber	0·012
5. Ashlar and brickwork in good order (cast and wrought iron)	0·013
6. Canvas hung on frames	0·015
7. Rubble in good order	0·017
8. Coarse rubble set dry, canals in perfect order in very firm ground	0·020
9. Canals in good order, free from weeds and stones ..	0·025
10. Canals in fair order, moderately free from weeds and stones	0·0275
11. Canals in bad order, obstructed by detritus	0·030
12. Rivers obstructed by detritus, canals in very bad order	0·035

From the calculated values of N given by Jackson for existing canals it appears that N = 0·025 is the coefficient applicable to main canals in Bengal, whilst, for distributaries which are not kept up to quite the same standard, N = 0·0275 would give more accurate result. In the North-West Provinces, Circular V. of the 11th November, 1874, N = 0·025 is suggested as the coefficient most generally applicable to canals in that province. Actual experiments with the object of determining the value of N for each main canal are very much to be desired.

For natural rivers the value of N varies from 0·022 to 0·035; where there is any detritus N = 0·03 is the coefficient found to be generally applicable; in other cases N = 0·0275 would probably be more correct.

The formula given above may be simplified for purposes of calculation by introducing a variable

$$M = N\left(41{\cdot}6 + \frac{0{\cdot}00281}{S}\right);$$

the discharge will then be given by the formula

$$Q = \frac{\sqrt{R}\,(M + 1{\cdot}811)}{N\,(M + \sqrt{R})}\,A\sqrt{RS}.$$

For purposes of calculation it is more convenient to have the formula in the shape $V = c \times 100\sqrt{RS}$, and this can be effected by making

$$c = \frac{\sqrt{R}}{100\,N}\left\{\frac{M + 1{\cdot}811}{M + \sqrt{R}}\right\},$$

in which case $V = c \times 100\sqrt{RS}$ and $Q = AV$.

In forms adapted for logrithmic computations these formulæ become

$$M = (41{\cdot}6\,N) + \left(\frac{1}{S} \times 0{\cdot}00281 \times N\right)$$

$$c = \left\{\frac{M}{N} + \frac{1{\cdot}811}{N}\right\} \times \sqrt{R} \times \frac{1}{M + \sqrt{R}} \times {\cdot}01, \text{ and } Q = A \times c \times 100\sqrt{RS}.$$

APPENDIX IV.

THE MISSISSIPI FORMULA FOR CALCULATING THE DISCHARGE OF RIVERS.

This formula is applicable to the case of large rivers only. Cunningham states that it seems probable that it gives as a rule fair approximations in cases of very low slope, but that as a general formula it is useless as a means of arriving at the mean velocity (Chapter XX., Section 24).

The formula involves a coefficient

$$k = \frac{1 \cdot 60}{\sqrt{R} + 1 \cdot 5}$$

and is

(1) For rectangular channels

$$V = \left\{ \sqrt{\cdot 0064\, k + (195\, R_1 \sqrt{S})^2} - \cdot 08 \sqrt{k} \right\}^2$$

(2) For river channels

$$V = \left\{ \sqrt{\cdot 0081\, k + (225\, R_1 \sqrt{S})^2} - \cdot 09 \sqrt{k} \right\}^2.$$

For large rivers where $R > 12$, the first term may be neglected.

(3) and the equation becomes

$$V = \left\{ (225\, R_1 \sqrt{S})^{\frac{1}{2}} - \cdot 0388 \right\}^2$$

(4) this expression approximates to $V = 15 \sqrt{R_1} \sqrt[4]{S}$, which differs in form from the Chezy formula in R_1 being substituted for R and $\sqrt[4]{S}$ for $\sqrt{S}$ in the variable part of the formula.

As used by Mr. Rhind in the report on the flood of the Mahanuddy it is—

(5) in the form

$$V = \left\{ \sqrt[4]{3 \cdot 0965\, R \sqrt{f}} - 0 \cdot 0388 \right\}^2.$$

f, the fall in feet per mile, being substituted for S in formula (3) and the constants modified accordingly, in the results 3 per cent. is deducted in cases where $R < 4$ feet, and 5 per cent. is deducted in cases where $R < 2$ feet.

APPENDIX V.

DISCHARGES OF RECTANGULAR ORIFICES AND OVERFALLS.

Notation.

Q = discharge in cubic feet per second.

c = coefficient of contraction.

h_1 = head at top of orifice; h_2 = head at bottom of orifice; h = any head; when $h_1 = o$, the orifice becomes an overfall, and $h_2 = d$, the depth of water above crest.

H = mean head at centre of orifice or difference between head and tail water.

w = width or length of orifice or overfall across its flow.

A = area = $w \times d$.

V = mean velocity through orifice or overfall.

u = mean velocity of approach; h_v = corresponding head.

u_1 = surface velocity of approach.

g = force of gravity = 32·2, $\sqrt{2g} = 8{\cdot}025$, $\frac{2}{3}\sqrt{2g} = 5{\cdot}35$.

I. Velocity of jet.

$$V = \sqrt{2gh},$$

and therefore

$$Q = c\,A\sqrt{2gh}.$$

II. The general formula for the discharge through an orifice is

$$Q = c \times \frac{2}{3} w \times \sqrt{2g} \times \left(h_2^{\frac{3}{2}} - h_1^{\frac{3}{2}}\right).$$

III. Relations between I. and II.

In formula II.—

$$h_2 = \left(H + \frac{d}{2}\right); \text{ and } h_1 = \left(H - \frac{d}{2}\right);$$

therefore

$$Q = c\sqrt{2gH} \times \frac{2}{3} A \left\{ \frac{\left(H + \frac{d}{2}\right)^{\frac{3}{2}} - \left(H - \frac{d}{2}\right)^{\frac{3}{2}}}{d\,H^{\frac{1}{2}}} \right\}$$

$$= \text{approximately } c\sqrt{2gH} \times A \times \left\{1 - \frac{d^2}{96\,H^2}\right\}$$

when H is large compared with d, the last term of this equation disappears and the equation becomes $Q = c.A.\sqrt{2gH}$, *vide* Neville, p. 49; also Unwin, Art. 35.

weir or overfall $h_1 = 0$ and equation II. becomes

$$Q = \epsilon \times \frac{2}{3} w \times \sqrt{2g} \times h_2^{\frac{3}{2}}$$

at

$$h_2 = d; \text{ and } w \times d = A;$$

therefore

$$Q = \epsilon \times \frac{2}{3} \sqrt{2gd} \times A$$

$$= w \times \frac{2}{3} \epsilon \sqrt{2g} \times d^{\frac{3}{2}}$$

$$= 5{\cdot}35 \times \epsilon \times w \times d^{\frac{3}{2}}$$

IV*a*. Taking into account obstructions such as piers, this formula, as given by Francis, becomes

$$Q = 5{\cdot}35 \times \epsilon \times (w - 0{\cdot}1\, n\, d) \times d^{\frac{3}{2}}$$

where n = number of obstructions, each pier counting as two, and the abutments as one each; in cases where the width of the channel and length of the weir-sill are equal, $n = 0$.

V. In a triangular notch, w being the width at top,

$$Q = \epsilon \times \frac{4}{15} w \sqrt{2g} \times d^{\frac{3}{2}}$$

where the angle is a right angle $w = d$; and

$$Q = \epsilon \times \frac{8}{15} \sqrt{2g} \times d^{\frac{5}{2}}$$

VI. For a submerged orifice or weir, where H becomes the difference between head and tail water—

$$Q = \frac{2}{3} \times \epsilon \times w \sqrt{2g} (H^{\frac{3}{2}} - h_1^{\frac{3}{2}}) + \epsilon \times w \sqrt{2g} H (h_1 - H),$$

but in the case of a weir $h_1 = 0$ and $h_2 = d$. Then

VI*a*. $$Q = \frac{2}{3} \epsilon \times w \sqrt{2g} \times H^{\frac{3}{2}} + \epsilon \times w \sqrt{2g} H (d - H),$$

where the value of the coefficient ϵ may vary in the two portions of the formula.

When the same coefficient is used, the formula becomes—

VI*b*. $$Q = \epsilon \times w \sqrt{2g} H \left(d - \frac{H}{3}\right).$$

Rise or afflux caused by weirs or obstructions:—

1st Form.—Free overfall—

$$Q = \frac{2}{3} c \times w \sqrt{2g} \times d^{\frac{3}{2}};$$

$$d = \sqrt[3]{\frac{Q^2}{\left(\frac{2}{3} c \cdot w\right)^2 \times 2g}}.$$

2nd Form.—Submerged weir—

$$Q = c \times w \sqrt{2g} H \left(d - \frac{H}{3}\right);$$

$$d = \frac{Q}{c \cdot w \sqrt{2g} H} + \frac{H}{3}.$$

In this case, H being the difference between head and tail water, will vary with d; the simplest way of proceeding is by assuming values of d, and testing them by the formula.

VIII. Velocities of approach.

Where the section of the orifice or weir is not small compared with the section of the channel, the velocity of approach must be taken into account. This velocity may be taken in terms of the head h_a expended in producing it.

$$h_a = \frac{v^2}{2g} = \frac{v^2}{64} = 0{\cdot}0155\, v^2,$$

and in the foregoing expressions the head h_a has to be added to any head in the formula which influences the discharge. The following formulæ suppose that the value of h_a has been actually measured; but in cases where the cross-section of the channel Ω only is known, it is best to proceed by approximation. Calculate [illegible]mate discharge Q' by Equation II. (or one suitable to the levels), then [illegible]g nearly. (Unwin, Art. 41.) This value of h_a, introduced into the equ[illegible] will give a second and much more approximate value of Q.

The foregoing equations, modified to include velocity of approach, become:

1*a*. When H is large compared with d

$$Q = c A \sqrt{2g\,(H + h_a)}.$$

2*a*. General formula for discharge through an orifice.

$$Q = \frac{2}{3} c \times w \sqrt{2g} \left\{(h_2 + h_a)^{\frac{3}{2}} - (h_1 + h_a)^{\frac{3}{2}}\right\}.$$

weir or overfall—

$$Q = \frac{2}{3} c \times w \sqrt{2g} \left\{ (d + h_v)^{\frac{3}{2}} - h_v^{\frac{3}{2}} \right\}.$$

II.(a). For a submerged weir or orifice (where c is taken to be the parts of the formula)

$$Q = c \times w \sqrt{2g} \left\{ (d + h_v)(H + h_v)^{\frac{1}{2}} - \frac{2}{3}(H + h_v)^{\frac{3}{2}} - \frac{2}{3} h_v^{\frac{3}{2}} \right\}.$$

VII.(a). Afflux caused by weirs and obstructions.

In this case it is best to work by a system of trial and error.*

The coefficient c for (I.) orifices and (II.) overfalls, may be taken in ordinary cases from the following tables:—

TABLE I.—ORIFICES.

Description.	c.	$c\sqrt{2g}$.
Orifices generally	·62 (c)	4·98
Sluices without side walls ..	·66	5·30
Canal lock and dock gates	·70	5·62
Sluices in lock gates	·83	6·66
Narrow bridge openings ..	·90	7·22
Very large well-built sluices with side walls	·94	7·54
Wide bridge openings ..		
Wide openings the bed of which is level with the bottom of the reservoir ..	·96	7·70

c may be modified in these cases so as to include velocity approach.

c_v is the new coefficient to be used in which account is taken the velocity of approach. Then:—

$$c_v = c\sqrt{1 + \frac{h_v}{H}}.$$

* Or D'Aubisson's formula may be used for an approximation—

$$Q = w \left\{ 3 \cdot 5 \, x \sqrt{x} + 0 \cdot 035 \, w^2 + 5 \, d_c \sqrt{x + 0 \cdot 02 \, x} \right\}^x$$

where x = afflux and d_c = depth of crest below original water surface.